Rio Tinto Alcan

Appendix 15-A

Underwater Noise Modelling

Savery & Associates Pty Ltd
Acoustic and Vibration Consultants

Piling Underwater Noise Modelling
South of Embley Project
Rio Tinto Alcan

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Prepared for:

Rio Tinto Pty Ltd

Level 3, 60 Albert Street

Brisbane QLD 4000

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SAVERY & ASSOCIATES PTY LTD

Suite 4, The Gap Village

1000 Waterworks Road

The Gap QLD 4061

PO Box 265,

The Gap QLD 4061

Telephone: (07) 3300 6288

Facsimile: (07) 3300 0574

E-mail: enquiry@savery.com.au

Report Author: Dr Marshall Hall

Peer Reviewer: Dr Alec Duncan, Curtin University

Project Manager: Matthew Terlich

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Executive Summary

Introduction

This report has been prepared to determine impact distances adjacent to offshore pile driving, associated with construction works for the Rio Tinto Alcan South of Embley project, over which aquatic animals are likely be disturbed or injured.

In the context of underwater noise, the term 'injury' includes partial deafness, whether temporary or permanent. Predictions are made of the underwater noise to be emitted from piling activities during construction of the offshore facilities planned for the Project and their locations are shown in Figure 1 in Appendix A. Their positions are listed in Table E1, in order of increasing longitude (west to east).

Table E1: Positions of the offshore facilities

Facility	Location
Port facility (Stage 1)	On coast between Boyd Point and Pera Head
Humbug barge terminal	Embley River
Hornibrook ferry/tug terminal	Embley River
Navigation Aid (#1)	Embley River
Navigation Aid (#2)	Embley River
Navigation Aid (#3)	Embley River
Hey River ferry/barge terminal	Hey River

The sizes of piles to be driven at the port facility are listed in Table E2. The provisional length of each pile is 30 m.

Table E2: Port facility piles

Facility	Diameter (mm)	Number of Piles
Main Wharf	1200	20
	1050	64
Dolphin	1500	36
(cluster of piles to serve as a fender)	1200	60
Approach Jetty	1050	38
Port Tug Depot	750	40
	600	2
	355.6	3
Port Navigation Aids	1050	5
	750	6

The sizes of the piles to be driven for the four river facilities are listed in Table E3. At the river facilities underwater noise levels were determined for a range of pipe pile diameters between

600mm and 1050mm, and 600mm AZ sheet piles, even if not included within the layout of the facility.

Table E3: River Facility piles

Facility	Diameter (mm)	Length (m)	Number of Piles
Humbug barge terminal	750	30	12
	900	30	6
	600 (Z profile AZ28)*	12.5	160
Humbug barge terminal (temporary berthing facility)	600	15	4
Hornibrook ferry/tug terminal	750	30	13
	1050	35	8
Hey River barge/ferry terminal	750	30	11
	900	30	6
	1050	30	1
	600 (Z profile AZ28)*	12.5	160
Hey River ferry/barge terminal (temporary berthing facility)	600	15	16
Navigation Aids	1050	30	3

* Note Z profile piles are sheet piles which are 600 mm in length rather than diameter

The pipe piles would be driven with hydraulic impact hammers. There would be up to three impact piling rigs in operation at the Port facility. There would be up to two impact piling rigs operating within the river, but only one hammer would be operating at a particular facility at any one time.

If required, the Drive-drill-drive method would be used in more challenging ground conditions. If pile driving refusal occurs above the target depth, the inside of the pile and remaining substrate would be drilled to target depth. Final re-drive into the open socket can then achieve pile penetration to the target depth.

In addition, 160 “Z profile AZ28” sheet piles, to produce a wall 110 m wide, may be installed using a vibratory driver at both Humbug Point and Hey River..

Due to differences in sound signals generated from the various sources, noise levels shall be assessed as multi-pulse signals for impact pile driving and as non-pulse signals for vibratory pile driving and drilling as described in Southall *et al*. (2007). The pulse/non-pulse distinction is important because the different signals generally have a different potential to cause physical effects, particularly on hearing.

Impacts of Underwater Noise on Marine Mammals

In order to quantify the assessment of potential disturbance or injury of piling noise to aquatic species, appropriate parameters are to be calculated.

Many acoustic metrics (including sound pressure, peak sound pressure or sound energy) could be considered in relation to noise impacts on animals. Southall *et al.* (2007), and more recently Erbe (2012), both identify that impact assessment in regards to behaviour disturbance should be multi-variate. However, Southall *et al.* (2007) identified sound pressure level as the best metric with which to assess the available behavioural response data, given it had most often been measured or estimated during disturbance studies.

Southall *et al.* (2007) used a dual-criterion approach to determine the recommended injury criteria. That is, any received noise exposure that exceeds either a peak pressure or a sound exposure criterion for injury is assumed to cause tissue injury in an exposed marine mammal, and the more precautionary of the two outcomes accepted.

In summary, according to Southall *et al* (2007) (pages 434-436), the appropriate parameters for describing impacts on mammals are as follows:

- Behaviour disturbance – RMS Sound Pressure Level [SPL]. The SPL (dB re μPa^2) that gives rise to a Response score of 6 as established by Southall *et al*. (2007) (Table 4, page 450) will be referred to as the critical value.
- Injury - Peak Sound Pressure Level [P-SPL] (dB re μPa^2), and Sound Exposure Level [SEL] (dB re $\mu Pa^2.s$). The P-SPL and SEL values that give rise to a small Temporary Threshold Shift will be referred to as the critical values.

These parameters are to be calculated according to the sound source level of piling and transmission loss in the ocean area based on the sound propagation model selected.

Noise impacts have been assessed for species identified as known to occur or likely to occur within the Project area. These species are identified below in Table E4. Estimates of their cruising speeds have been provided to determine the likely duration of the species exposure, and therefore potential for injury, due to piling noise.

Southall *et al*. (2007) distinguishes between "low-frequency" (LF), "mid-frequency" (MF) and "high-frequency" (HF) cetaceans, on the basis of the frequency band of the animal's audiogram. The three bandwidths are LF = 7 Hz – 22 kHz; MF = 150 Hz – 160 kHz; and HF = 200 Hz – 180 kHz (op. cit., page 430). Of the three cetacean species considered (Table E4) the baleen whale is LF and the two dolphin species are MF. Audiograms for the specific species in Table E4 are unavailable, however comparable audiograms for similar species are shown in Figure 22.

Table E4: Species groups of aquatic animals potentially impacted by construction noise

Animal group	Individual species affected	Potential Geographic distribution within project area	Estimated cruising speed [km/hr]
Whale	Bryde's (baleen)	Port	5 while feeding (DSEWPAC, 2008)
Dolphin	Indo-Pacific Humpback, Australian Snubfin	Port & river facilities	8 (Seaworld San Diego)
Dugong	Dugong	Port (migrating) and river facilities	10 (Australianfauna.com)
Turtle	Hawksbill, Flatback, Olive Ridley, Leatherback, Loggerhead, Green.	Port & river facilities	2 (Wikipedia)
Sawfish	Dwarf, Green, Freshwater	Port & river facilities	1 (DSEWPAC, 2008)
Shark	Speartooth	River facilities	8 (Wikipedia)
Crocodile	Estuarine	Port & river facilities	5 (Wiki.answers.com)

Piling Noise Source Levels and Frequency Spectrum

Sound source level during impact piling was predicted based on past measurements and corresponding regression equations. To obtain the regression equations for SEL source level (SELSL) and P-SPL source level (P-SPLSL), 15 measurements were used by applying the International Mathematics & Statistics Library (IMSL) least-square routine RGIVN to the data with a Log HE coefficient of 10 (Nehls *et al*. 2007).

The resulting regression equation for SELSL is:

$$\text{SELSL (dB re } \mu\text{Pa}^2\text{.s)} = 10 \log \text{HE} + A + B \times \log \text{PD} + C \times \log \text{SFD} \qquad \text{(E1)}$$

where A = 149, B = 9.6 and C = -0.90 and estimated standard deviation of the model is 4.06 dB

The regression equation for P-SPLSL is:

$$\text{P-SPLSL (dB re } \mu\text{Pa}^2\text{)} = 10 \log \text{HE} + D + E \times \log \text{PD} + F \times \log \text{SFD} \qquad \text{(E2)}$$

where D = 183, E = 6.6 and F = 3.1 and estimated standard deviation of the model is 4.73 dB.

The IMSL routine RSTAT was applied to the outputs of RGIVN to obtain the standard deviation.

To allow for uncertainty in the regression estimate the source levels were increased to a 95% confidence level. Using the regression equations (3) and (4), and correcting for uncertainty in the regression equation the source level of both sound exposure levels and peak sound pressure level were calculated for the purpose of impact evaluation for aquatic animals during piling. The pile source levels are shown in Table E5.

Table E5: Pile source levels and acoustic datum positions

Facility	Pile diameter (mm)	Acoustic datum	SFD during HAT (m)	Predicted SELSL per blow, dB re μPa^2.s.	Predicted P-SPLSL, dB re μPa^2.
Port Facility	1500	West end of wharf	20.9	211	242
	1200			210	241
	1050			207	239
	750			206	238
	600			206	236
	356			203	235
Humbug barge terminal	600	South end of dredging area	5.4	206	235
	750			206	236
	900			207	236
	1050			208	237
	Sheet pile			SPLSL = 185	202
Humbug barge terminal (temporary berthing facility)	600	East end of Humbug barge terminal	≤5.4	205	235
Hornibrook ferry/tug terminal	600	South end of tug depot dredging area	10.6	206	235
	750			206	237
	900			207	237
	1050			208	238
Navigation Aid #1	1050		9.5	208	238
Navigation Aid #2	1050		11.3	208	238
Navigation Aid #3	1050		15.4	208	238
Hey River barge/ferry terminal	600	East end of dredging area	5.4	206	235
	750			206	236
	900			207	236
	1050			208	237
	Sheet pile			SPLSL = 185	202
Hey River barge/ferry terminal (temporary berthing facility)	600	South end of Hey River facility	≤3.9	205	235

The theoretical frequency spectrum of the noise from driving pipe piles is a fundamental frequency (at approximately 80 Hz for a 30-m pile) together with a sequence of harmonics whose relative amplitudes decrease as – 20 log (frequency). For calculating the noise at various ranges, the spectrum is described in terms of third-octave bands; and the band-levels generally decrease with frequency, except in those bands that do not contain any harmonic (the 100, 125 and 200-Hz bands), and also between neighbouring bands where the number of harmonics increases (which occurs between the 500 and 630-Hz bands).

There is insufficient information available for producing regression equations for vibratory hammers. According to ICF Jones and Stokes and Illingworth and Rodkin, Inc (2009), using a vibratory hammer to drive an AZ steel sheet pile (0.6 m wide) generated maximum values of 202 dB re μPa^2 for P-SPLSL, and 185 dB re μPa^2 for SPLSL. As can be seen from Table E5, this P-SPLSL is 33 dB less than the corresponding source level for pipe piles that are to be driven at the facilities where a vibratory hammer is to be used (Humbug and Hey River). As a vibratory hammer produces a continuous (although unsteady) noise, it is inappropriate to assign a source level for SEL.

Drilling would be used in challenging ground conditions when the Drive-drill-drive method is required. The P-SPLSL from drilling of a socket for a pile would be no more than the value of 163 dB re μPa^2 from published reports. On comparing this with the quietest predicted P-SPLSL for driving pipe piles of 202 dB re μPa^2 (Table E5), it can be seen that drilling noise is at least 39 dB quieter. It is noted that drilling would not reduce P-SPL experienced during the installation of a pile (if the "Drive-drill-drive" method is required); since driving would be resumed once drilling is completed. Drilling could however reduce the cumulative SEL emitted during the installation of a pile.

Modelling Methodology

Since the seafloor depth varies with position, as may the acoustic properties of the seabed, it is necessary to use "range-dependent" models that cater for variations with position along the propagation path. The models selected here are "Adiabatic Modes Based on Orca" (AMBO), and "ORCA" to model propagation along the deepest propagation path. AMBO model neglects mode coupling, which can be important when a property such as seafloor depth changes rapidly with position. The popular alternative model is one of the "Range-dependent Acoustic Model" (RAM) family of Parabolic-Equation (PE) models, which do include mode coupling due to small slopes. Unlike AMBO however, no single RAM model is able to cater for both the low shear-speeds that occur in mud, as well as the high shear speeds that occur in rock. Propagation loss can be predicted given the geo-acoustic parameters of the seabed, water properties and the corresponding bathymetry data. The accuracy of the AMBO model was benchmarked against a RAM model to determine the effect of the steep sides of the dredge channel. Minor differences between the two models were considered negligible and the AMBO model considered more suitable as identified above.

Based on the AMBO model, SEL contours and peak SPL contours were calculated separately at the Port, Humbug barge terminal, Hornibrook ferry/tug terminal and Hey River ferry/barge terminal over the horizontal plane. The SEL contours for a single hammer blow are shown in Figure 12 and Figure 15 to Figure 17. Contours for P-SPL at each facility are presented in Figure 18 to Figure 21. Since the modelling produces results for SEL but not SPL, a relationship was derived between SEL and SPL for pile-driving noise. To achieve this, data for both have been obtained from three reports on pipe piles (Duncan et al 2010, Erbe 2009, and ICF Jones and Stokes and Illingworth and Rodkin, Inc 2009). The result of plotting SEL vs. SPL is shown in Figure 2. If it is assumed that the ratio (difference in dB) of SEL to SPL is constant, then the curve of best fit to the data is:

$$SEL = SPL - 13.1 \qquad \text{(E3)}$$

There is little corresponding information on sheet piles. According to ICF Jones and Stokes and Illingworth and Rodkin, Inc (2009, page I-64), SEL was 13 dB lower than the SPL. This is therefore consistent with Eq. (E3).

Mitigation Options

In order to reduce the piling noise level, potential mitigation options have been assessed through review of previous published studies. Potential options considered include cushions, bubble screens, soft start-up procedures and acoustic mitigation devices. Of these methods cushions and soft-start up procedures were determined to be potentially effective. Implementation of bubble curtains was considered, however the method requires maintaining a high air fraction in the water close to the pile, which is often impractical when the Project operating environments are exposed to tidal and ocean currents.

Potential noise reduction achievable from use of pile cushions of different materials are presented in Table E6.

Table E6: Cushion details and expected reductions

Material	Disk thickness (mm)	Number of disks in cushion	Reduction in SPL (dB)	Reduction in SEL (dB)
Plywood	100	3 or 4	11 - 26	11 – 13
Micarta	25	Not reported	7 - 8	6 – 7
Nylon	50	Not reported	4 - 5	6 – 8

Previous studies identified that marine mammals may be deterred from pile driving activity by a soft start procedure (Bailey *et al.* 2010; Robinson *et al.* 2007; Nehls *et al.* 2007). A soft start-up involves progressively increasing hammer energy and therefore noise levels to alert animals to the commencement of the operations. The distance of potential injury to an animal is therefore reduced while deterring animals from the operations outside of this distance.

Examples of soft start procedures reviewed included piling commencing with hammer energy levels 1/8th and 1/10th of maximum energy. These examples would result in a reduction of 9 dB and 10 dB reduction of source levels respectively.

Through reduction of source levels these mitigation options have potential to decrease the distance of injury (determined by SEL and P-SPL) and behaviour disturbance (determined by SPL) for aquatic mammals.

Critical Values

As identified previously criteria for injury and behavioural disturbance have been determined as critical values. The critical values have been determined from Southall *et al.* (2007) for injury (pages 437-445) and behaviour disturbance (pages 446-473). The critical values are presented in Tables E7 and E8 for the species groups identified in Table E4.

<u>Behaviour Disturbance</u>

It is important to identify that from the perspective of behavioural ecology, an effect (e.g. a short term avoidance behaviour) does not necessarily equate to a negative impact on the animal (including its welfare) (Beale 2007). That is, undertaking an avoidance behaviour is only important if it alters the fitness of an individual through changing foraging rates or reproductive output. The assessment approach undertaken reflected the need to focus on impacts that are ecologically meaningful.

Critical values for behaviour disturbance are expressed in terms of SPL only (Southall *et al*, page 452). Within Southall *et al.* (2007) (Tables 6-9, pages 453-456 & Tables 14-17, pages 461 to 466) behavioural responses of LF & MF cetaceans to multiple pulses and non-pulses from published sources were categorised against the determined severity scale (Table 4, Page 450). The reported SPL's were assessed to determine the reasonable SPL which is unlikely to cause a Response score of 7 or more and is thus suitable as the critical value. The determined SPL's for LF and MF cetaceans were taken as the Critical SPL and are presented in Table E7. These Critical SPL's were subsequently used to determine impact distances of behaviour disturbance for aquatic mammals.

The conclusion drawn by Southall *et al*. (2007) that cetacean behaviour disturbance is determined by SPL alone, is assumed to apply to the remaining species also. Typical audiograms for the Speartooth Shark and the sawfish species were assessed for comparison to the audiogram for LF cetaceans, in regards to the spectrum of the animals hearing bandwidth as well as hearing threshold over the bandwidth of intense pile driving noise. The Critical SPL for these species was assumed to exceed that of the LF cetacean by the difference in their average hearing thresholds. The critical value for turtles was taken as an average of the estimation based upon hearing threshold comparison and a critical value from a published study. The determined SPL's for these species groups are presented in Table E7.

Table E7: Critical behaviour disturbance values .

Signal type:	Multiple pulse Critical SPL (dB re μPa^2)	Non-pulse Critical SPL (dB re μPa^2)
LF Cetacean	165	135
MF Cetacean & Dugong	177	177
Turtle	175	150
Sawfish	215	185
Shark	210	180

Underwater noise is not identified as a potential impact on Estuarine Crocodiles (Leach *et al.* 2009) nor is it identified as a threat to the species in the DSEWPaC SPRAT database (DSEWPaC 2012). Crocodiles are known to occur within the vicinity of the port facilities within the Embley River, where similar construction and operational activities have been conducted. Similarly, the species would be expected to continuing utilising environments surrounding the Project marine facilities.

Injury

Criteria for injury due to multiple pulses are expressed in terms of both P-SPL and cumulative SEL (Southall *et al*, page 443).

The critical P-SPL's for MF and LF cetaceans were obtained from Southall *et al.* (2007) (Table 3, page 443). The determined critical P-SPL is 230 dB re μPa^2 for both LF and MF cetaceans.

SEL is a measure of the energy of the sound which an animal would be exposed to. Avoidance of a loud sound source is common to a wide range of disturbance responses. In estimating injury in terms of SEL it is necessary to consider the cumulative SEL that an animal would be exposed to as it moves away from the sound source.

As an animal moves away from the sound source, the perceived SEL per blow would gradually decrease with each succeeding blow and therefore the rate at which cumulative SEL (as perceived by an individual animal) increases with time would decrease. However, the calculation of cumulative SEL neglects the gradual decrease and hence over-estimates the perceived SEL. The cumulative SEL would also be calculated on the assumption that the animal remains at the impact distance that produces a disturbance Response score of 6, for the duration required for it to travel 2 km. These assumptions would over-estimate the cumulative SEL likely to be perceived by an animal, providing a conservative estimate.

For multi-pulse noise sources (pile driving) the cumulative SEL an animal is exposed to for a given number of blows of equal magnitude would be increased by 10 log (number of blows). This relationship was used to determine the critical SEL per blow for piling through:

$$\text{Critical SEL per blow} = \text{Critical cumulative SEL} - 10 \log(\text{number of blows}) \qquad \text{(E4)}$$

The critical cumulative values for MF and LF cetaceans are provided by Southall *et al.* (2007) (Table 3, page 443). As was done for behaviour disturbance the critical values for LF cetaceans were weighted by the audiogram for each species to obtain the relevant single-blow criteria.

The Critical cumulative SEL and Critical SEL per blow for injury proposed for each species for multiple pulse sources are presented in Table E8.

Table E8: Critical cumulative injury values for multiple pulses signals.

Animal group	Duration (hours) *	Number of blows	Critical cumulative SEL (dB re µPa^2.s)	Critical SEL per blow (dB re µPa^2.s)
LF Cetacean	0.4	44	198	182
MF Cetacean & Dugong	0.25	27	200	186
Turtle	1	110	213	193
Sawfish	2	220	248	225
Shark	0.25	27	243	228

* Duration required to travel 2km

Since non-pulse noise sources (drilling and vibratory hammer) produce a continuous noise, it is appropriate and possible to consider injury impacts from the cumulative SEL an animal may be exposed to over a given duration. As the critical SPL for non-pulse sounds is known (Table E7) the cumulative SEL can be calculated by the following relationship between SEL and SPL for a steady noise of duration T.

$$SEL = SPL + 10 \log T \qquad (E5)$$

As an example the cumulative SEL for low frequency cetaceans would be calculated as:

Cumulative SEL = 135 dB re µPa^2 + 10 Log (1440) = 167 dB re µPa^2.s

The cumulative SEL values for each species group are presented in Table E9 below, along with the critical cumulative values. The MF and LF cetaceans critical cumulative values are provided by Southall et al. (2007) (Table 3, page 443). As was done for behaviour disturbance the critical values for LF cetaceans were weighted by the audiogram for each species to obtain the relevant criteria.

Table E9: Critical cumulative disturbance and injury values for non-pulse signals

Animal group	Duration T (s)	Critical disturbance nonpulse SPL (dB re µPa^2)	Disturbance Cumulative SEL* (dB re µPa^2.s)	Critical injury Non-pulse cumulative SEL (dB re µPa^2.s)
LF cetacean	1440	135	167	215
MF cetacean & dugong	900	177	207	215
Turtle	3600	150	186	230
Sawfish	7200	185	224	265
Shark	900	180	210	260

* = SPL(critical disturbance nonpulse) + 10 log T. Example : 135+10log(1440)=167

Impact Distances

As identified above impact distances are determined for behaviour disturbance based upon the determined Critical SPL values. Impact distances for injury were determined based upon the Critical SEL per blow for pile driving and cumulative SEL over the duration of exposure of each species for drilling and vibratory hammer activities. The impact distances correspond to where the acoustic variables (SPL, P-SPL or SEL) equal their corresponding critical value, and represent the distance from the activity at which each species would be impacted by the piling operation. This distance is determined from the noise propagation modelling AMBO model, the output of which is presented in Figure 12 and Figure 15 to Figure 17 (SEL contours) for each of the facilities. Contours are produced for the largest pile at each facility; however, impact distances for the smaller piles at each facility have been determined from the known difference in the source levels (Table E3).

An assessment was conducted to determine the change in received noise levels at varying receiver depths along the deepest modelled noise propagation path at each facility. At the Port along the dredge channel (bearing of 298^{o}), received levels were predicted to increase by 5 dB at a depth of 11m over those at 3 m. At this deeper receiver, sound propagation is expected to be greatest along the dredge channel than on other bearings, due to the greater depth of the dredge channel relative to the surrounding sea floor in the vicinity of the port. Received levels were predicted to increase up to 1 dB at Humbug, up to 4.5 dB at Hornibrook, up to 1.5 dB at Hey River and up to 4.0 dB at the river Navigation Aids. Modelling was repeated, using ORCA, to predict these higher received levels at each facility.

The associated impact distances to manage behavioural disturbance were greater along the deepest propagation path than in other directions and are identified in Tables E10 to E14 as conservative impact distances for Project piling operations. Impact distances are assessed for each species and for each pile size / type to allow for effective management of impacts from operations. The estimated distances that would apply through implementation of pile cushions. Thick wood pile cushion (TWPC) & Thick micarta pile cushion (TMPC) are presented as applicable to the broadest pile. The impact distances for the more slender piles would be reduced proportional to this example if mitigated. The calculated impact distances, based upon the worst-case simultaneous operation of all three pile rigs, is also shown in Table E10.

Table E10: Disturbance-based impact distances (Port facility)

Animal group	Drilling	Impact Distance Single rig driving							Impact Distance Triple rig driving
		Driving unmitigated					Driving 1500 mitigated		Driving unmitigated
		1500	1200	1050	750	356	TMPC	TWPC	1500 plus two 1050
LF Cetacean	30	1330	1210	930	790	570	700	400	ESLBES; 1580 IOD
MF Cetacean & dugong	<1	400	360	270	230	170	210	130	500
Turtle	<10	470	430	350	280	210	250	150	630
Sawfish	<1	<10	<10	<10	<10	<10	<10	<10	<10

TMPC = Thick micarta Pile Cushion, TWPC = Thick wood pile cushion.

Table E11: Disturbance-based impact distances (Humbug barge terminal).

Animal group	Impact distance (m)							
	Drilling	Driving unmitigated					Driving 1050 mitigated	
		Sheet	600	750	900	1050	TMPC	TWPC
MF Cetacean & Dugong	<1	<10	130	140	160	170	80	40
Turtle	<10	60	160	180	200	210	100	50
Sawfish	<1	<10	<10	<10	<10	<10	<10	<1
Shark	0	<10	<10	<10	<10	<10	<10	<10

Note: The impact distances here have their maximum values in the West direction.

Table E12: Disturbance-based impact distances (Hornibrook ferry/tug terminal)

Animal group	Drilling	Impact distance (m)					
		Driving unmitigated				Driving 1050 mitigated	
		600	750	900	1050	TMPC	TWPC
MF Cetacean & Dugong	<1	190	210	230	250	100	60
Turtle	<10	240	280	310	340	150	70
Sawfish	<1	<10	<10	<10	<10	<10	<1
Shark	0	<10	<10	<10	<10	<10	<10

Note: The impact distances here have their maximum values in the South-west direction.

Table E13: Disturbance-based impact distances (Hey River ferry/barge terminal)

Animal group	Drilling	Impact distance (m)						
		Driving unmitigated					Driving 1050 mitigated	
		Sheet	600	750	900	1050	TMPC	TWPC
MF Cetacean & Dugong	0	<10	300	330	360	380	200	90
Turtle	<10	110	370	400	440	470	250	120
Sawfish	0	<10	<10	<10	<10	<10	<10	<1
Shark	0	<10	<10	<10	<10	<10	<10	<10

Note: The impact distances here have their maximum values in the North and South directions.

Table E14: Disturbance-based impact distances (Navigation Beacons)

Animal group	Drilling	Impact distance (m)		
		Driving unmitigated	Driving 1050 mitigated	
		1050	TMPC	TWPC
MF Cetacean & Dugong	0	280	150	60
Turtle	<10	360	170	70
Sawfish	0	<10	<10	<1
Shark	0	<10	<10	<10

A check has been undertaken to determine whether, for any animal group, the impact distance based on injury exceeds the distance based on disturbance.

For assessing injury, the relevant parameters are P-SPL and SEL. The impact distance defined by P-SPL is given by:

$$\text{P-SPLSL} - \text{P-SPL(critical)} = 20 \log (\text{impact distance}) \qquad \text{(E6)}$$

The critical P-SPL for cetacean species is 230 dB re μPa^2. The maximum value of P-SPLSL amongst the six facilities is 242 dB re μPa^2, and the corresponding impact distance is 3 m. Therefore no impact distance would be required at any facility on the basis of P-SPL alone. As was done for behaviour disturbance, audiogram comparison for the remaining species indicates that the critical P-SPL would increase for all remaining species. No impact distance would be required for the remainder of the species.

To calculate the impact distance required on the basis of SEL, the Cumulative SEL of each species was determined in Table E8. For pile driving if each animal were positioned at their disturbance distance, the SEL they would perceive for each hammer blow would be numerically 13 dB less than the multi-pulse SPL values listed in Table E7. The resultant SEL values are all 20 to 30 dB less than the corresponding values for critical injury SEL per blow listed in Table E8. The largest impact distance for injury is 31m for the LF cetacean for the largest pile (1500mm) at the Port, Impact distances for all other pile sizes at all other facilities and for all other species would be smaller.

To assess injury due to SEL exposure from non-pulse sources the cumulative SEL was determined. Comparison of cumulative SEL values with the non-pulse Critical SEL values in

Table E9 it can be seen that cumulative SEL are smaller than the Critical SEL. For the majority of species groups except for the MF Cetacean & Dugong, the durations would have to be increased by a factor of at least 100 before the SEL injury criterion would result in a larger impact distance than the disturbance criterion.

It is concluded that in the context of the present report impact distances are larger for behaviour disturbance than injury.

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1.0 Introduction

This report has been prepared by Savery & Associates Pty Ltd for Worley Parsons Services Pty Ltd, to determine impact distances adjacent to offshore pile driving, associated with construction works for the Rio Tinto Alcan South of Embley project, over which aquatic animals are likely be disturbed or injured. In the context of underwater noise, the term 'injury' includes partial deafness, whether temporary or permanent. Predictions are made of the underwater noise to be emitted during construction of eight facilities identified in Section 2.0 below.

2.0 Marine facilities and positions

The marine facilities and river navigation aids planned for the South of Embley Project and their locations are shown in Figure 1 in Appendix A. Their positions are listed in Table 1, in order of increasing longitude (west to east).

Table 1: Positions of the offshore facilities

Facility	Location
Port facility (Stage 1)	Between Boyd Point and Pera Head
Humbug barge terminal	Embley River, west of existing Humbug Point wharf
Hornibrook ferry/tug terminal	Embley River, east of Lorim Point wharf
Navigation Aid (#1)	Embley River
Navigation Aid (#2)	Embley River
Navigation Aid (#3)	Embley River
Hey River ferry/barge terminal	Hey River, south of Hey Point

Stage 1 of the port facility includes an approach jetty, a two-berth wharf with a single ship-loader. The seafloor would be dredged to create adjacent berthing pockets and an approach channel on a bearing of 298°. The length of the wharf /jetty is 944 m, of which 100 m is ashore. Later, should Stage 2 of the Port be constructed, an additional 2 berths would be added, extending the wharf by an additional 358m.

The river facilities are each confined to comparatively small regions.

3.0 Pile driving

For the purposes of modelling pile driving has been assessed over a 12 hour period each day.

3.1 Pile driving for Port facility

The diameters of the piles to be driven at the port facility are listed in Table 2. The provisional length of each pile is 30 m.

Table 2: Diameters and quantities of Port facility piles

Location	Diameter (mm)	Number of Piles
Main Wharf	1200	20
	1050	64
Dolphin	1500	36
(cluster of piles to serve as a fender)	1200	60
Approach Jetty	1050	38
Port Tug Depot	750	40
	600	2
	355.6	3
Port Navigation Aids	1050	5
	750	6

The large 1200 and 1500-mm piles are expected to be driven by a Junttan HHK-25S pile driver or equivalent. This hammer has a mass of 25 tonnes and a maximum drop height of 1.5 m, yielding an energy of 368 kJ.

Piles more slender than 1200 mm are expected to be driven by a 16-tonne Juntuan Hammer (another Hydraulic Drop hammer) or equivalent, which has an energy of 235 kJ.

In general, two or three hammers would be in use simultaneously at the Port: one 25-tonne, and one or two 16-tonne.

Noise levels would be determined over distances up to around 1500 m centred at the west end of Stage 1 of the proposed wharf. This position is selected as the “acoustic datum” position since the broadest piles would be driven there, and it is the closest construction point to most animals that might happen to be in the vicinity during pile driving.

The construction of this wharf is part of Stage 1 of the South-of Embley project, and further construction in the proximity of this wharf is expected to occur during a subsequent Stage 2. The results to be presented in the present report for Stage 1 should be applicable to Stage 2, subject to the following conditions:

- The different geographical positions of the piles are taken into account
- The seafloor topography relative to the Stage-2 piles is similar to that relative to Stage 1
- The piles have the same diameters as those used in Stage 1
- The hammers have the same energies as those used in Stage 1.

3.2 Pile driving for the River Facilities

The sizes of the pipe piles to be driven for the three river facilities and navigation aids are listed in Table 3.

Table 3: Sizes and quantities of River Facility piles

Facility	Diameter (mm)	Length (m)	Number of Piles
Humbug barge terminal	750	30	12
	900	30	6
	600 (Z profile AZ28)*	12.5	160
Humbug barge terminal (temporary berthing facility)	600	15	4
Hornibrook ferry / tug terminal	750	30	13
	1050	35	8
Hey River ferry/barge terminal	750	30	11
	900	30	6
	1050	30	1
	600 (Z profile AZ28)*	12.5	160
Hey River ferry/barge terminal (temporary berthing facility)	600	15	16
Navigation Aids	1050	30	3

* Note Z profile piles are sheet piles which are 600 mm in length rather than diameter

At the river facilities underwater noise levels were determined for a range of pipe pile diameters between 600mm and 1050mm, and 600-mm AZ sheet piles, even if not included within the layout of the facility (refer Section 6.0).

For pipe piles, two hammers would be in use simultaneously, but only one hammer would be operating at a particular facility at any one time. Each hammer is expected to be a 16-tonne Juntuan impact hammer.

In addition, “Z profile AZ28” sheet piles, to produce a wall 110 m wide, would be installed using a vibratory driver at both Humbug Point and Hey River. These sheet piles are interlocking steel “AZ”-type piles, 630 mm wide, and 12 m long. They weigh 2 tonnes each, and would be installed to a depth of 6 m. A typical type of Vibratory Driver that would be used for the sheet piles is the ICE® Model 44B made by International Construction Equipment Inc. This driver has a maximum frequency of 1800 vibrations per minute (30 Hz) and a driving force of 1844 kN (188 tonnes weight).

3.3 Impacts of underwater noise on aquatic animals

The aquatic animal groups and individual species that may be disturbed or injured by the construction noise are listed in Table 4. Their geographic distribution within the project area is included. Estimates of their cruising speeds have been added, since the likely duration of their exposure to construction noise will be determined by this parameter.

Table 4: Groups and species of aquatic animals liable to be affected by construction noise, and their cruising speeds.

Animal group	Individual species affected	Potential Geographic distribution within project area	Estimated average cruising speed [km/hr]
Whale	Bryde's (baleen)	Port	5 (DSEWPaC, 2008)
Dolphin	Indo-Pacific Humpback, Australian Snubfin	Port & river sites	8 (Seaworld San Diego)
Dugong	Dugong	Port and river sites	10 (Australianfauna.com)
Turtle	Hawksbill, Flatback, Olive Ridley, Leatherback, Loggerhead, Green.	Port & river sites	2 (Wikipedia)
Sawfish	Dwarf, Green, Freshwater	Port & river sites	1 (DSEWPaC, 2008)
Shark	Speartooth	River sites	8 (Wikipedia)
Crocodile	Estuarine	Port & river sites	5 (Wiki.answers.com)

The objective of the present assessment is to define impact distances for the first six animal groups listed in Table 4.

Loud underwater sounds can disturb the behaviour of aquatic animals. Southall *et al.* (2007, page 449) developed an ordinal ranking of behavioural response severity with "response scores" from 0 to 9. "The intent of this scaling was to delineate those behaviours that are relatively minor and/or brief (scores 0-3); those with higher potential to affect foraging, reproduction, or survival (scores 4-6); and those considered likely to affect these vital rates (scores 7-9)". Examples of disturbed behaviour include avoidance of the sound source, separation of females from dependent offspring, and cessation of reproductive behaviour (from the list in Southall *et al*. 2007, page 450). A score of 0 corresponds to "no observable response" while a score of 9 corresponds to "outright panic, flight, stampede,… stranding…".

It is important to identify that from the perspective of behavioural ecology, an effect (e.g. a short term avoidance behaviour) does not necessarily equate to a negative impact on the animal (including its welfare) (Beale 2007). That is, undertaking an avoidance behaviour is only important if it alters the fitness of an individual through changing foraging rates or reproductive output. The assessment approach undertaken reflected the need to focus on impacts that are ecologically meaningful. For the present report, it will be assumed that it is acceptable to cause a Response Score of 6, which corresponds to several behaviours that include "minor or moderate avoidance of sound source, brief or minor separation of females and dependent offspring, aggressive behaviour related to noise exposure, extended cessation or modification of vocal behaviour, visible startle response, and brief cessation of reproductive behaviour".

Very loud sounds can cause injury, which usually refers to permanent or temporary threshold shift (partial deafness). The terms "loud" and "very loud" will be quantified as appropriate later in the report.

Many acoustic metrics (including sound pressure, peak sound pressure or sound energy) could be considered in relation to noise impacts on animals. Southall *et al.* (2007), and more recently Erbe (2012), both identify that impact assessment in regards to behaviour disturbance should be multi-variate. However, Southall *et al.* (2007) identified sound pressure level as the best metric with which to assess the available behavioural response data, given it had most often been measured or estimated during disturbance studies. There are limitations associated with this method including that sound pressure level fails to account for the duration of exposure whereas this is captured using sound exposure level, and that many other contextual variables may affect behaviour disturbance. However, more recent or relevant data to the listed threatened or migratory species in the Project area are not available and therefore it is concluded that sound pressure level is still currently the best metric with which to assess the available behavioural response data.

Southall *et al.* (2007) used a dual-criterion approach to determine the recommended injury criteria. That is, any received noise exposure that exceeds either a peak pressure or a sound exposure criterion for injury is assumed to cause tissue injury in an exposed marine mammal, and the more precautionary of the two outcomes accepted.

In summary, according to Southall *et al*. (pages 434-436), the appropriate parameters for describing impacts on mammals are as follows:

- Behaviour disturbance – RMS Sound Pressure Level [SPL] (the symbol SPL without any qualifier will denote RMS SPL). The SPL that gives rise to a Response score of 6 will be referred to as the critical value.
- Injury - Peak Sound Pressure Level [P-SPL], and Sound Exposure Level [SEL]. The P-SPL and SEL values that give rise to a small Temporary Threshold Shift will be referred to as the critical values.

The legislative requirement is that the project be approved under both the *Environment Protection and Biodiversity Conservation Act 1999* (Cth), and the *State Development and Public Works Act 1971* (Qld). The relevant government agencies are the Commonwealth Department of Sustainability, Environment, Water, Population and Communities (DSEWPaC), and the Queensland Department of State Development, Infrastructure and Planning.

For the animal groups listed in Table 4 (other than the crocodile), the information required to determine impacts has been obtained from the sources listed in Table 5.

Table 5: Sources of information on impact of loud noise on the various animal groups.

Animal group	Source
Whale and dolphin	Southall *et al*. (2007)
Dugong (represented by West Indian Manatee)	Gerstein (1999)
Turtle	McCauley et al (2000), Tech Environmental, Inc (2006)
Sawfish (represented by Yellow stingray)	Casper (2006)
Shark (represented by Nurse shark)	Casper (2006)

4.0 Modelling Methodology

Noise levels will be determined over sectors of at least 1500-m distance centred at the acoustic datum of each proposed facility (except where truncated by a shoreline). Where channels are to be dredged, estimates will take account of such channels, since sound propagates at least as strongly along deeper channels as it does in shallower regions.

4.1 Computing Sound Exposure Level

At a distance from a source that radiates a transient pulse of noise, the pressure pulse waveform is the fluctuation in received pressure. Sound Exposure Level (SEL) is the energy of this pressure pulse waveform (which is equal to the area under the square of its Fourier transform).

By convention, SEL at 1 m is used to describe the sound energy emitted by the source. This is known as the energy Source Level, and is denoted here as SELSL.

The Fourier Transform (FT) of the pressure waveform at frequency (f) and distance d is given by:

$$10 \log|FT(f,d)|^2 = 10 \log|FT(f,1)|^2 - PL(f,d),$$

where

FT(f,1) is the Fourier Transform of the pressure pulse waveform at a reference distance of 1 m (as inferred from measurements at distances in the far-field; not necessarily the actual waveform that would be measured at 1 m), and

PL(f,d) is the Propagation Loss at frequency f from 1 m to distance d.

If the pressure pulse waveform at distance d is denoted by p(t,d) then SEL is defined as 10 log of the integral over time of $p^2(t,d)$, which also equals the integral over frequency of $|FT|^2$.

Since PL is a function of frequency, the shape of the SEL spectrum will vary with distance. The effect of this variation will be taken into account in the calculations that are described later in this report.

To estimate the cumulative SEL for a number of blows of equal magnitude, 10 log (number of blows) should be added to the single-blow value. The appropriate number is the number of blows that occur over the “exposure time” during which pile driving continues unabated and individual animals remain at approximately the same distance from the sound source. If there are large underwater obstructions in the propagation paths, then the number would be reduced depending on the cross-sectional area of such obstructions.

According to Southall *et al.* (page 499) “The SEL metric also enables integrating sound energy across multiple exposures from sources such as seismic airguns, pile driving, and most sonar signals”. The cumulative SEL of N pulses, as defined by Southall, is the sum of the SELs of the N pulses. “This summation procedure essentially generates a single exposure “equivalent” value that assumes no recovery of hearing between repeated exposures” (Southall op cit, page 500).

When two hammers are operating simultaneously, the SELs from each must be summed, according to the rule for adding quantities expressed in dB:

$$SEL(sum) = 10 \log (10^{SEL1/10} + 10^{SEL2/10}) \quad (1)$$

For example, if the two SELs are equal, then the sum would be 3 dB greater than either of them. If one of the SELs exceeds the other by at least 10 dB, then the sum would equal just the higher value; the effect of the lower SEL would be less than 0.4 dB and thus negligible.

4.2 Computing Peak SPL

The peak sound pressure level (P-SPL) is the maximum value of the fluctuation in the pressure waveform (whether positive or negative). P-SPL at 1 m is used to describe the peak SPL emitted by the source; it is known as the pressure Source Level, and is denoted here as P-SPLSL. To obtain Peak SPL at distance d rigorously, it is necessary to compute the inverse Fourier transform of FT(f,d) to obtain p(t,d), and then determine the maximum value of p. This requires that a model of the complex (magnitude and phase) function FT(f,1) be available, although normally only the magnitude is provided by measurements. The phase component can be hypothesized, but since the peak of a function is sensitive to errors, this is not a robust method. The approach used here, which can be used because the maximum distance of concern is 1 km and seawater is iso-speed (the sound-speed is approximately constant from the sea surface to the seafloor) or isothermal for three of the four seasons, is to model Peak SPL as spherical spreading, until the seafloor depth is shallow enough to cause cut-off at the predominant frequency. To model the attenuation rate of P-SPL in very shallow water, the contours have been computed using the following algorithm:

First, the wideband PL at distance d is defined by

$$PL_{wb}(d) = SELSL – SEL(d).$$

Then P-SPL is assumed to follow spherical spreading where PL_{wb} < spherical spreading; but where PL_{wb} > spherical spreading (indicative of very shallow water) then P-SPL is assumed to decay with range at the same rate as SEL.

$$P\text{-}SPL(d) = P\text{-}SPLSL – 20 \log d, \qquad \text{if } PL_{wb}(d) < 20 \log d,$$

$$P\text{-}SPL(d) = P\text{-}SPLSL – PL_{wb}(d), \qquad \text{if } PL_{wb}(d) > 20 \log d.$$

The rationale is that PL_{wb} being less than 20 log d corresponds to SEL being augmented by reflections at boundaries, which do not augment P-SPL. PL_{wb} exceeding 20 log d is indicative of a weakening of the pulse that will also lessen its P-SPL.

When two hammers are operating simultaneously, the P-SPL would generally be unaffected, since the timing of the blows by one hammer is independent of the timing by the other. At a given position, two pulses might occasionally arrive at the same time, and in this event the peak pressure could be greater than that of either of the pulses if the difference in arrival times is less than around the period of the usual peak frequency of pile-driving spectra. The maximum P-SPL that might arise in this manner would be at a position where the individual P-SPLs are equal, in which case the P-SPL of the combined pulse would be 6 dB greater than that of either. According to Figure 14 the peak frequency is spread from 630 to 2500 Hz after propagating over a distance of around 1 km, giving an average period of approximately 1 millisecond. Since the average delay between pulses is of the order of 1 second, the probability of two pulses arriving within 1 millisecond is of the order of 0.001 (1 out of every 1000 blows). The increase in P-SPL would be significant only at positions close to mid-way between the two hammers, and would occur for around only 1 out of every 1000 blows. It is concluded that the likelihood of impact of such increases in P-SPL on aquatic fauna are negligible.

4.3 Computing SPL

Since the modelling will produce results for SEL but not SPL, it is necessary to derive a relation between SEL and SPL for pile-driving noise. To achieve this, data for both have been obtained from three reports on pipe piles (Duncan *et al*. 2010, Erbe 2009, and ICF Jones and Stokes and Illingworth and Rodkin, Inc. 2009). The result of plotting SEL vs. SPL is shown in Figure 2. The first of the ICF Jones and Stokes and Illingworth and Rodkin, Inc (2009) examples used a pile cushion made of wood; all other examples were unmitigated. The low results from Erbe (2009) were measured at distances of approximately 1300 m. If it is assumed that the ratio (difference in dB) of SEL to SPL is constant, then the curve of best fit to the data is:

$$\text{SEL} = \text{SPL} - 13.1. \qquad (2)$$

This function is shown in Figure 2, where it is evident that it will be as good a fit to the data as any other. Of the 22 points, 80% (18) lie within 2 dB of this straight line. Eighty percent of the effective pulse durations therefore lie in the interval $10^{-1.31 \pm 0.2}$ s, or from 30 to 80 ms, with an average of $10^{-13.1/10}$ s = 49 ms.

There is little corresponding information on sheet piles. According to ICF Jones and Stokes and Illingworth and Rodkin, Inc. (2009, page I-64), SEL was about 25 to 27 dB lower than P-SPL and 13 dB lower than the RMS level . This latter result is consistent with Eq. (2).

When two hammers are operating simultaneously, the value of SPL would be larger, and still be obtained from Eq. (2).

4.4 Source Levels of Pile driving noise

4.4.1 Pipe piles

Data for SEL reported from hammering of steel pipe piles have been collated from 15 measurements at short distances and converted to SELSL by computing PL at frequencies from 80 Hz to 12.5 kHz). ORCA uses the given seafloor depths and estimates the appropriate geoacoustic models, and computes the area under each spectral curve to estimate SEL. ORCA is an accurate PL model that will be described further in section 4.6. The sources of these data are Bailey *et al*. (2010), Carlson *et al*. (2007), Duncan *et al*. (2010), Erbe (2009), ICF Jones and Stokes and Illingworth and Rodkin, Inc (2009) and Laughlin (2007). Except for Bailey, whose minimum measurement distance was 100 m, the measurement distances were all less than 40 m. In selecting from the ICF Jones and Stokes and Illingworth and Rodkin, Inc (2009) data, the single case that included a wood pile cushion was omitted. It has been assumed that the measurements from all other reports include a hammer cushion but not a pile cushion.

Results for P-SPL were also reported for the above measurements and converted to P-SPLSL by assuming spherical spreading to the shortest measurement distance.

Associated parameters that are commonly reported and considered to be potential predictors of radiated noise are pile diameter (PD), hammer energy (HE), and seafloor depth (SFD). These three parameters are listed in Table 6, together with their respective units and ranges (minima and maxima), as obtained from the reports of the 15 measurements.

Table 6: Ranges of parameters during 15 measurements of unmitigated Source Levels.

Parameter	Unit	Ranges
Pile diameter (PD)	mm	356 - 1800
Hammer energy (HE)	kJ	62 - 360
Seafloor depth (SFD)	m	1 - 42
SELSL	dB re $\mu Pa^2.s$	193 - 209
P-SPLSL	dB re μPa^2	221 - 237

Regression equations for SELSL and peak SPLSL have been derived by applying the International Mathematics & Statistics Library (IMSL) least-square routine RGIVN to the data referred to in Table 6. For the form of the regression equation, it has been assumed that the sound energy (expressed in $\mu Pa^2.s$ rather than dB re $\mu Pa^2.s$) would be linearly proportional to the hammer energy (Nehls *et al*. 2007), and proportional to unknown powers of pile diameter and seafloor depth. The decibel measure of SELSL would then be expressed as the sum of four terms, a constant (intercept), and three terms which would each be a coefficient times the logarithm of the parameter (for hammer energy, the coefficient is fixed at 10). The resulting regression equation for SELSL (using the 15 observations) is:

$$SELSL = 10 \log HE + A + B \times \log PD + C \times \log SFD, \qquad (3)$$

in which (to 2 or 3 significant figures) A = 149, B = 9.6 and C = -0.90. Since there is scatter in the regressions, it is necessary to treat SELSL as a random variable. A result computed with Eq. (3) will be the mean value of SELSL's probability distribution, and will be the approximate median of that distribution.

The IMSL routine RSTAT was applied to the outputs of RGIVN, in order to obtain the standard errors of the estimates and the estimated standard deviation of model error (ESDOME). The standard errors of A, B and C are 17, 5.9 and 2.5 respectively, and ESDOME = 4.06 dB. If the probability distribution of SELSL around its mean value were approximately Gaussian, then there would be a chance of approximately 5% that SELSL will exceed that predicted by Eq. (3) by more than $1.65 \times 4.06 = 6.7$ dB (for a random variable that has a Gaussian distribution with unit standard deviation, 1.65 is the level that has a cumulative probability of 95%). Although the distribution of SELSL is likely to be different from Gaussian, the uncertainty estimate is expected to be similar (the appropriateness of the Gaussian distribution has been supported by a histogram of the residuals obtained when the 15 "fitted" SELSLs were computed using Eq. (3) and subtracted from the corresponding observed values; according to this histogram, one out of the 15 residuals (7%) exceeded 6.7 dB). It will therefore be assumed that 5% of perceived SELs will exceed predictions based on Eq. (3) by at least 6.7 dB. This uncertainty will be taken into account in determining the impact distances by augmenting individual SELSLs by 6.7 dB, so that animals at the impact distance will have only a 5% chance of perceiving an SEL greater than the critical value.

For P-SPLSL it was assumed that sound intensity or mean square pressure (expressed in μPa^2 rather than dB re μPa^2) would be linearly proportional to hammer energy. The regression equation produced by RGIVN is:

$$\text{P-SPLSL} = 10 \log \text{HE} + \text{D} + \text{E} \times \log \text{PD} + \text{F} \times \log \text{SFD}, \tag{4}$$

in which D = 183, E = 6.6 and F = 3.1.

According to the RSTAT routine the standard errors of D, E and F are 20, 6.9 and 2.9 respectively, and ESDOME = 4.73 dB. There will be a chance of approximately 5% that P-SPLSL exceeds that predicted by Eq. (4) by more than $1.65 \times 4.73 = 7.8$ dB. This uncertainty will be taken into account in determining impact distances by augmenting individual P-SPLSLs by 7.8 dB, so that animals at the impact distance would have only a 5% chance of perceiving P-SPL greater than the critical value.

4.4.2 Sheet piles and vibratory hammer

Vibratory hammers use oscillatory hammers that vibrate the pile, causing the sediment surrounding the pile to liquefy and allow pile penetration. Peak sound pressure levels for vibratory hammers can exceed 180 dB re μPa^2; however, the sound from these hammers rises relatively slowly. The vibratory hammer produces sound energy that is spread out over time and SPL is generally 10 to 20 dB lower than impact pile driving (ICF Jones and Stokes and Illingworth and Rodkin, Inc. 2009). There is insufficient information available for producing regression equations. According to ICF Jones and Stokes and Illingworth and Rodkin, Inc (2009), using a vibratory hammer to drive an AZ steel sheet pile (0.6 m wide) generated maximum values of 202 dB re μPa^2 for P-SPLSL, and 185 dB re μPa^2 for SPLSL (these numbers were obtained by adding 20 dB to results at 10 m from ICF Jones and Stokes and Illingworth and Rodkin, Inc (2009)). It will be seen later in Chapter 6 (Table 10) that this P-SPLSL is 33 dB less than the corresponding prediction for the pipe piles that are to be driven at the facilities where a vibratory hammer is to be used (Humbug and Hey).

Since a vibratory hammer produces a continuous (unsteady) noise, it is inappropriate to assign a value for SEL. Since SEL is the integral over time of pressure-squared, the relation between SEL and SPL for a steady noise of duration T is:

$$\text{SEL} = \text{SPL} + 10 \log T \tag{5}$$

Although SPL is conventionally referred to as the decibel value of RMS pressure, it is actually the decibel value of mean-square pressure: SPL = 10 log (mean square pressure). Eq. (5) is applicable to both vibratory hammer noise and drill noise.

4.5 Spectrum of pile driving noise

At very short distances, the spectrum of noise radiated from a driven pipe pile will have its peak at the resonance frequency of the dominant mode of free vibration. According to Love (1944, pages 543-546) the vibration of a free (unclamped) slender cylindrical shell has two modes:

(i) almost purely radial (with a resonance frequency that depends on the Poisson ratio of the solid and varies inversely with the cylinder diameter), and

(ii) almost purely longitudinal, with a sequence of resonance frequencies given by

$$F_n = n \sqrt{(Y/\rho)} /2L, \qquad (6)$$

where Y and ρ are the solid's Young modulus and density, L is the cylinder length, and n is the sequence of positive integers. As remarked by Love (1944), "The latter are of the same kind as the extensional vibrations of a thin rod". Since the thickness of the shell has no effect, this resonance should be independent of the amount of any matter inside the cylinder, although the restraint on movement by the buried pile toe may affect the resonance. For typical values for Y and ρ for steel (200 GPa and 7800 kg/m^3), the results for the harmonics from 1 (fundamental) to 5 are shown in Figure 3. The pile lengths are either 15 m (600 mm piles at the temporary facilities), 35 m for the 1050-mm piles at Hornibrook terminal, and 30 m for all others (Tables 2 and 3). Their fundamental frequencies will therefore be either 169, 72 or 84 Hz, the second harmonics will be either 338, 144 or 168 Hz, the third harmonics either 506, 216 or 252 Hz, and so on. By comparison, the resonance frequency of the radial vibration of a 1500-mm diameter pile (for example) is around 1100 Hz. Since peak frequencies from pile-driving generally lie in the neighbourhood of 200 - 400 Hz (Bailey *et al*. 2010, Erbe 2009, Nehls *et al*. 2007, Reinhall and Dahl 2011), it follows that the set of harmonics of radial pulsation of the solid caused by the longitudinal vibration (by virtue of the pile's Poisson ratio) is the dominant radiator of sound into the seawater and seabed.

The noise spectra at the pile are assumed to consist of the sequence of harmonics defined by Eq. (6), the (linear) intensities of which vary as $1 /[250^2 + (2\pi F_n)^2]$. The basis of this frequency-dependence is that the pressure across the top of a pile during impact may be approximated by a step function of time followed by an exponential decay with a time constant of 0.004 s (Reinhall and Dahl, 2011). The wideband SELSL will therefore be given by:

$$SELSL = k + 10 \log (1 /[250^2 + (2\pi F_1)^2] + 1 /[250^2 + (2\pi F_2)^2] + 1 /[250^2 + (2\pi F_3)^2] + ..),$$

where k is a constant to be determined from results obtained for SELSL using Eq. (3). Since F_1 is typically around 100 Hz, 250^2 is small compared with $(2\pi F_n)^2$ for any n, and the decibel spectrum will be a sequence of lines whose relative amplitudes are approximately $-20 \log(F_n)$. A line spectrum of this nature is shown by Reinhall and Dahl (2011), who remark that "energy spectral density … will reveal this delay in the form of spectral interference peaks every 1/T Hz or 79 Hz … where T represents the nominal travel time of the bulge wave over twice the length of the pile".

For each pile, SEL could be computed by summing over the harmonics from the fundamental to the maximum frequency selected for analysis, which will be shown in section 4.6 to be 12.5 kHz. This method would require processing approximately 12500 /80 = 156 frequencies, and the individual frequencies would vary from one pile to another, depending on pile length. Of the 156 frequencies, 37 would lie in the 12.5 kHz third-octave band alone (the width of any third-octave band is 23.6% of the centre frequency, which is nearly 3 kHz for the 12.5-kHz band). The method adopted instead has been to group the harmonics into the standard third-octave bands, and to process the 23 such bands from the 80-Hz band to the 12.5-kHz band (some longer piles would also require the 63-Hz band to be included if treated individually). An example of the third-octave band-level spectrum that results is shown by the blue curve in Figure 14. This example applies to a case where the wideband SELSL is 211 dB re $\mu Pa^2.s$ and the pile length is 30 m, yielding a fundamental frequency of 84 Hz (which lies in the 80-Hz third-octave band). Three bands (100, 125 and 200 Hz) contain no harmonic, as indicated by the absence of data marks. Six bands contain one harmonic each (80, 160, 250, 315, 400 and 500 Hz), and most bands starting from 630 Hz contain two harmonics. Except for a small peak in the 630-Hz band and the three nulls, the band-level spectrum decreases monotonically with frequency.

The practical significance of pile length is that fundamental frequencies of the order of 100 Hz exhibit low-frequency cut-off in shallow water, and thus the noise from a long pile will be lost into the sea/river bed more-so than for a shorter pile. In order to ensure that the noisiest case is catered for, it is therefore necessary that modelling of radiated noise be based on the minimum length that is to be used for each diameter.

4.6 Propagation loss

If the acoustic properties of the seabed and ocean are known then the propagation loss from a point source may be computed using a suitable mathematical model. Since the seafloor depth varies with position, as may the acoustic properties of the seabed, it is necessary to use models that cater for variations with position along the propagation path (referred to as "range-dependent" models in the underwater acoustics literature). The model selected here is "Adiabatic Modes Based on Orca" (AMBO), which has been subjected to peer-review and benchmarking (Hall, 2004). AMBO uses the normal-mode underwater acoustic propagation model "ORCA" (Westwood *et al*. 1996) to compute the mode properties at waypoints along a propagation path, and then uses adiabatic mode theory to compute PL at any position. AMBO neglects mode coupling, which can be important when a property such as seafloor depth changes rapidly with position. The popular alternative model is one of the "Range-dependent Acoustic Model" (RAM) family of Parabolic-Equation (PE) models (Collins 1998), which do include mode coupling due to small slopes (slope is the dimensionless ratio of the change in seafloor depth to the corresponding change in horizontal displacement). However, unlike AMBO, no single RAM model is able to cater for both the low shear-speeds that occur in mud, as well as the high shear speeds that occur in rock.

AMBO was selected for the following reasons:

(i) the effect of mode-coupling on SEL is expected to be small, given that the seafloor slopes (further described in Section 5.2) are smaller than 0.3 and maintain a maximum value of 0.3 over small distances (less than 15m along the sides of the channel to be dredged). An indicator of the significance of mode coupling is given by a "Coupling effect" (CE), defined by:

$$CE = C_{21} \times RI,$$

in which RI is the horizontal range interval of the slope and C_{21} is the coupling coefficient between modes 1 and 2 (coupling is higher between modes 1 and 2 than it is between any other pair of modes). From an expression for C_{21} (Hall, 1986), it can be shown that CE is given by:

$$CE = 8/3 \times DI / DVFS,$$

where DI is the depth increment encompassed by the slope and DVFS is the depth of the virtual free surface, as defined by Weston (1960) and evaluated by Hall (1986).

In order to obtain benchmarks for what values of CE constitute insignificant and significant mode coupling, an example of each has been examined as presented by McDaniel (1982). The effect of coupling on the sound field beyond the steep section was negligible when CE = 0.76 and significant when CE = 2.29. For the Port channel scenario, the depth increment is 4.7 m and DVFS (at 200 Hz) is 30 m, giving CE = 0.4. It follows that the effect of mode coupling on the sound field beyond steep sections should be insignificant in the present scenario. This expectation has been checked by running both AMBO and RAMS (a version of RAM that caters for a high shear speed, but not for both high and low shear speeds in different layers) for a homogenous solid seabed with sound and shear speeds characteristic of the basement at Port (2300 and 1210 m/s respectively). In the present study, the steepest seafloor occurred along a bearing of 118° at a distance of 400 m from the Port acoustic datum, as shown by the red curve in Figure 6. As the horizontal distance increased from 390 to 415 m, the depth decreased from 20.9 to 13.1 m. AMBO and RAMS both produced localised peaks in SEL beyond the change in slope, although the AMBO peak at 415 m was 20 m closer than the RAMS peak. At greater distance however the two models were in good agreement.

(ii) ORCA caters for an adequate range of shear-speeds in the seabed, and

(iii) ORCA runs fast, finds as many modes as required, and is very accurate.

(iv) From the list of propagation models in the “Ocean Acoustics Library” (http://oalib.hlsresearch.com), alternative models such as PECAN and MMPE are potentially useful. Both however use the “complex density” method (Zhang and Tindle 1995) to simulate shear in the seabed, and this method is accurate only for shear speeds up to 1000 m/s.

The AMBO output files (one for each frequency) along each propagation path from acoustic datum contained PL at range steps of 5 m. These data were supplied to synthesizing programs that:

- smoothed each curve of PL versus distance over third-octave (24%) windows (to simulate a third-octave frequency average);
- integrated over frequency to produce SEL at each range along the path; and
- produced a contour plot of SEL centred on the acoustic datum.

The calculations will be based on the bathymetry-distance profiles that apply during HAT.

It has been observed that due to the phenomenon of low-frequency cut-off in shallow water propagation, the contribution of frequencies below 100 Hz to wideband SEL at distances of interest is generally small, even though the noise spectrum at the pile may have its maximum at such frequencies. Nevertheless the calculations of SEL will include all harmonics of the pile vibration down to the fundamental frequency. It has also been found that due to the phenomena of absorption in seawater and frequency-dependent bottom reflectivity, together with the fall-off in the pile vibration as frequency increases, the contribution of frequencies above 12.5 kHz to wideband SEL at distances of interest is negligible. The calculations of SEL will therefore exclude the harmonics that lie beyond the 12.5 kHz third-octave band.

4.7 Geo-Acoustic Model of the seabed

A geo-acoustic model (GAM) is the set of all the acoustic properties of the seabed, expressed as a set of layers overlying a basement. The layers correspond to the stratigraphy that would be revealed by seismic refraction profiling (if conducted), and the basement is the uniform medium below the deepest layer. For each layer and basement, the five acoustic properties (sound and shear speeds, sound and shear absorption coefficients, and density), are specified, and for each layer the thickness is also specified. Layers need not be homogeneous; for an inhomogeneous layer the value of each property at both the top and bottom are specified.

4.7.1 Seismic profiling

Seismic refraction data are available in the vicinity of the port facility. These data yield the sound-speeds at the tops of the layers and basement where there are discontinuities in the sound speed profile. The modelling method adopted was that for each layer and basement, the porosity was estimated from the corresponding sound-speed, using appropriate regression equations (Hamilton 1980, Richardson and Briggs 1993). Porosity is not used by the propagation model, but is the key used to produce estimates of the other acoustic properties, again using published regression equations (except for the shear absorption coefficients, for which an in-house expression was used).

Although spatial variation in seafloor depth has been catered for, it has been assumed that the GAM does not vary spatially. This assumption will be further discussed in the Data Inputs chapter.

4.7.2 Moisture Content

If seismic refraction data are unavailable, an alternative method of deriving a GAM is to use data for Moisture Content, defined as the ratio of mass of water to mass of solid. If the density of water and solid are known or assumed, then porosity (p) may be determined from Moisture Content (c). From the definition of Moisture Content, it follows that:

$$c = p\,\rho w / [(1 - p)\,\rho s]$$

where ρs is density of the solid, and ρw is density of water. Re-arrangement of this expression yields:

$$p = \rho s\, c / (\rho s\, c + \rho w). \qquad (7)$$

From porosity, the GAM is estimated as described above for seismic profiling.

5.0 Data Inputs

5.1 Water properties

In this summary, temperatures will be reported in °C and salinities in Practical Salinity Units, which are equivalent to parts per thousand. Temperature and salinity were measured during October 2007 at five nearby offshore positions, and at one position near the Hey River ferry terminal. At the sea surface, the median water temperature was 28° offshore and 29° in Hey River, while the median salinity was 35 ppt offshore and 36 ppt in Hey River (RTA 2011). Near the seafloor, the median water temperature was 27° or 28° offshore, and 29° near the ferry terminal, while the median salinity was 35 ppt.

Temperature and salinity profiles (with depth) vary with season of the year, and for the calculations of acoustic PL that will be described in Chapter 6, it is necessary to take into account the profiles that will result in the lowest values of PL. Climatology data over all four seasons have therefore been obtained from the World Ocean Atlas, averaged over the 5-degree square centred on 13°S, 141°E. The data are grouped into seasons, defined as quarters of the calendar year: Q1 is Jan - Mar, Q2 is Apr - Jun, Q3 is Jul - Sep, and Q4 is Oct - Dec. It has been noted that in the top 20 m, the temperature is approximately constant with depth, and its average varies seasonally between 26° in Q3 and 29° in Q1. During Q4 the average temperature is 28°, consistent with the results measured during October 2007. The salinity is generally constant with depth, and its average varies seasonally between 34 ppt in Q1 and 35 ppt in Q3. During Q4 the WOA salinity ranges between 33 ppt and 35 ppt, the latter being consistent with the results measured during October 2007. Sound-speed profiles computed from these data are shown in Figure 4 in Appendix A. For each season two curves are shown; one is the mean plus one standard deviation and the other is the mean minus one standard deviation. Except for Q4, the water to a depth of 20 m is approximately iso-speed. In the top 20 m, the average sound-speed over the four quarters is 1539.5 m/s, and this value has been used in the PL model.

5.2 Bathymetry

5.2.1 Port Facility

According to Coffey (2009, page 9):

> "Offshore at the site of the jetty and main wharf, the sea bed falls at a grade of some 1(v) in 60 (h), to a depth of some 13m below Chart Datum, where the sea bed levels out to about a 1 in 600 slope.

Contours from a detailed bathymetry survey conducted by 3D Marine Mapping Pty Ltd are shown in Note: Shows location of proposed wharf and jetty in stages

Figure 5 in Appendix A. The contour interval is 1 m. The depths are corrected to Chart Datum, which is approximately Lowest Astronomical Tide (LAT). The proposed Stage 1 wharf/jetty is approximately 940 m long on a bearing of 298°, and around 100 m of the jetty is onshore.

Although bathymetry data pertains to LAT, it is necessary to estimate the maximum seafloor depths that occur during Highest Astronomical Tide (HAT), since sound generally propagates in deeper water at least as strongly as it does in shallower water. The difference between HAT and LAT at the proposed wharf is 3.1 m (RTA 2011).

An important feature of bathymetry is that berthing pockets and a channel would be dredged before the pile driving begins, to allow bauxite ore carriers to berth and load along either side of the jetty, and depart. The channel floor would be 17.8 m deep during LAT (20.9 m during HAT), would extend on a bearing of 298° from 600 m offshore out to around 1600 m (where the seafloor falls to that depth). An angle of 18° would be used for the underwater dredged slopes.

The bathymetry has been sampled at waypoints along paths from the west-end of the wharf, on 36 bearings in 10 deg. steps, and taking into account the proposed dredging, and converted from LAT to HAT. The results at four bearings commencing from acoustic datum are shown in Figure 6 in Appendix A. Two (118° and 298°) are parallel to, and two (028° and 208°) are perpendicular to, the line of the proposed wharf.

5.2.2 Humbug & Hornibrook Facilities

Bathymetric maps of the western Embley River near these facilities are shown in Figure 7. The difference between HAT and LAT at these terminals is 3.4 m (RTA 2011).

From the perspective of the proposed Humbug terminal, sound paths on a bearing of less than 160° are blocked by Humbug Wharf (in this analysis, bearings are rounded to the nearest 10°). As the bearing is increased from 160°, SFD during LAT at a distance of 1000 m commences at 5 m and decreases to a minimum of 0.5 m at 240°, a high point of Cora Bank. As bearing is further increased, SFD increases and reaches a maximum of 12 m in a channel at a bearing of 270°. The depth then decreases as the shoreline is approached on a bearing of 290°. The ensonified zone is therefore a sector with an apex angle of 130°.

From the perspective of the proposed Hornibrook terminal, the minimum bearing along which sound paths remain waterborne out to around 1000 m is 120°. As the bearing is increased from 120°, SFD during LAT at a distance of 1000 m commences at 0 m and increases to a maximum of 10 m at 150°, and then decreases to a minimum of 2 m on Cora Bank at a bearing of 260°. As bearing is further increased, SFD increases and reaches a maximum of 13 m in a channel at a bearing of 290°. The depth then decreases until the path runs parallel to (and close to) the Lorim Point Wharf on a bearing of 300°. The ensonified zone is therefore a sector with an apex angle of 180°.

5.2.3 Hey River and Navigation Aids

A bathymetric map of the region of the Hey River that includes the proposed ferry terminal and the three proposed Navigation Aids (in the Embley River, near the mouth of the Hey River) is shown in Figure 7. From the Hey River terminal, the ensonified sector ranges over bearing from 10° to 170°.

5.3 Geology

5.3.1 Port Facility

Seismic refraction profiling produced results for layers of fixed sound-speed along a line corresponding to the proposed jetty/wharf (Coffey 2008, page 23), and seismic reflection profiling determined the thickness of the unconsolidated mud layer along a line out to 7 km from shore (Worley Parsons 2010, page 15), on the wharf/jetty bearing of 298°. A slow spatial variation in the thickness of this unconsolidated layer is evident. Given that the maximum distance of concern has been specified as 1000 m, the procedure adopted was to select the thickness applicable at a distance of 500 m out from the west end of the wharf (0.4 m), as representing an average along the 1000-m propagation path (no seismic data is available at positions further than 200 m from the 118°-298° line). Below the mud layer, the sound speed increased suddenly to 1900-m/s in a layer that Coffey described as calcareous sand.

Coffey also describes a sound speed of 2300 m/s for “medium to high strength weathered siltstone/sandstone rock” (Coffey 2008, page 8). The GAM as supplied to the PL model therefore contains two inhomogeneous layers (mud and sand) and a basement of denser rock, the top of which is 24 m below the seafloor. The numeric details are displayed in Table 7. The discontinuities in each property between layers are represented by showing their values above and below the interface depth (for both 0.4 m and 24 m).

Table 7 shows that sound-speed, shear-speed and density all increase monotonically with depth, whereas the absorption coefficients have a maximum at the bottom of the mud layer (depth 0.4 m -). The reason is that absorption has a maximum at a porosity of 0.52 (Hamilton 1980, page 1328). The maximum occurs because absorption is due to flow of viscous seawater between grains; at low porosity there is little flow, and at high porosity the flow is less affected by viscosity (the velocity gradient is smaller). Like sound-speed, the porosity at the bottom of the mud layer has a discontinuity and its values above and below that depth (estimated from sound-speeds of 1600 and 1900 m/s) are 0.55 and 0.16 respectively. The bottom of the mud layer is therefore the closest to having a porosity of 0.52. A plot of the estimated porosity profile is shown in Figure 8.

Table 7: Geo-acoustic model used in the PL model at the Port Facility

Depth below seafloor, m	Sound-speed, m/s	Shear-speed, m/s	Density, kg/m^3	Sound absorption, dB/λ	Shear absorption, dB/λ
0	1560	0	1671	0.492	0
0.4-	1600	98	1777	1.037	3.65
0.4+	1900	1000	1973	0.875	0.862
24-	2200	1158	2160	0.786	0.774
24+	2300	1210	2196	0.759	0.748

5.3.2 Humbug barge terminal & Hornibrook ferry/tug terminal

Two offshore drill holes (DH501 and 503) were completed near Hornibrook (Coffey, 2009). The Moisture Contents measured at depths from 1 to 30 m have been converted to porosities and the resulting profiles are shown in Figure 9. From the profiles of Moisture Content provided, an average profile was constructed. From this average profile a GAM consisting of three layers and a basement has been computed, and the numeric details are listed in Table 8. There are discontinuities in this GAM.

Shallow riverbed samples (in the top metre of the riverbed) have been taken at both Humbug and Hornibrook by Worley Parsons (WP), and the average Moisture Contents are consistent between the two facilities (46 and 45%), although Humbug exhibited more variability (37 – 53%) than Hornibrook (42 – 47%, with an outlier at 31%). The WP results at Hornibrook are less than the single Coffey result obtained 1 metre deep in Drill Hole 503 (58%). Nevertheless, if the variability is allowed for, it is reasonable to conclude that the Humbug riverbed is similar to the Hornibrook riverbed. Since no data is available from offshore drill holes near Humbug, Hornibrook data will be assigned to that nearby facility as well.

Table 8: The Geo-acoustic model used in the PL model at Hornibrook ferry and tug terminals and Humbug barge terminal

Depth below river-floor, m	Sound speed, m/s	Shear speed, m/s	Density, kg/m^3	Sound absorption, dB/λ	Shear absorption, dB/λ
0	1560	0	1671	0.471	0
10	1593	229	2247	0.460	2.664
15	1584	195	1906	0.946	3.650
30	1628	329	2296	0.394	1.881

5.3.3 Hey River ferry/barge terminal

Three offshore drill holes (DH508, 509 and 516) were completed near the proposed Hey River ferry/barge terminal (Coffey, 2009), and Moisture Contents were measured at depths from 3 to 22 m. WP have taken seven shallow riverbed samples at Hey River, and the Moisture Contents measured in the top 0.8 m of the riverbed range between 29 and 39%. The Moisture Content profiles have been converted to porosities, and are shown in Figure 10. The average of the Coffey profiles has been merged with the average of the WP results, and from this a GAM consisting of three layers and a basement has been computed, the numeric details of which are listed in Table 9. There are no discontinuities in this GAM.

Table 9: The Geo-acoustic model used in the PL model at Hey

Depth below river-floor, m	Sound speed, m/s	Shear speed, m/s	Density, kg/m^3	Sound absorption, dB/λ	Shear absorption, dB/λ
0	1664	0	1903	0.950	0
4	1685	187	2146	0.640	3.65
13	1690	208	1945	0.900	3.65
22	1725	320	2306	0.390	1.972

6.0 Source Levels of the pile-driving scenarios

In listing predicted Source Levels for the various pile-driving scenarios, this report will consider the driving of the different pile diameters at each facility. Of the piles, those selected for analysis are those most exposed to open water where large animals are most likely to be present. The most exposed position would also be in the deepest of the floor depths that occur over the extent of the facility. For the pile sizes and hammer energies as listed in section 3.2, the selected positions acoustic datums (position of the most exposed and broadest pile) at each site, sea floor depth and predicted Source Levels are listed in Table 10. As described in Section 3.2, at the river facilities (Humbug, Hornibrook and Hey River) a range of pipe pile diameters between 600mm and 1050mm and 600mm AZ sheet piles were assessed, even if not included within the layout of the facility. The same size piles have slightly different source levels at the different facilities because of differing seafloor depths (SFD) at the planned pile positions. The expressions for SL include terms in SFD: SELSL according to Equation (3), and P-SPLSL according to Equation (4). Source levels are presented for the entire range of assessed piles. For the pipe piles, the values are obtained from Eqs. (3) and (4) and augmented by 1.65 × ESDOME to yield the 95% confidence levels.

Each position will be referred to as the “acoustic datum” for that facility. The seafloor depths listed are those in the dredging plans.

The 25-tonne hammers include a hammer cushion of diameter 1050 mm, which is assumed to be 41mm thick and made of nylon (Nylatron MC904P) (Hammersteel 2006). This cushion is assumed to have the same effects on the SELSL and P-SPLSL of this hammer as did the hammer cushions included in the observations referred to in Table 6.

Table 10: Acoustic datums, seafloor depths, and pile driving source levels

Facility	Pile diameter (mm)	Acoustic datum	SFD during HAT (m)	Predicted SELSL per blow, dB re $\mu Pa^2.s$.	Predicted P-SPLSL, dB re μPa^2.
Port Facility	1500	West end of wharf	20.9	211	242
	1200			210	241
	1050			207	239
	750			206	238
	600			206	236
	356			203	235
Humbug barge terminal	600	South end of dredging area	5.4	206	235
	750			206	236
	900			207	236
	1050			208	237
	Sheet pile			SPLSL = 185	202
Humbug barge terminal (temporary berthing facility)	600	East end of Humbug barge terminal	≤5.4	205	235
Hornibrook ferry/tug terminal	600	South end of tug depot dredging area	10.6	206	235
	750			206	237
	900			207	237
	1050			208	238
Navigation Aid #1	1050		9.5	208	238
Navigation Aid #2	1050		11.3	208	238
Navigation Aid #3	1050		15.4	208	238
Hey River barge/ferry terminal	600	East end of dredging area	5.4	206	235
	750			206	236
	900			207	236
	1050			208	237
	Sheet pile			SPLSL = 185	202
Hey River barge/ferry terminal (temporary berthing facility)	600	South end of Hey River facility	≤3.9	205	235

7.0 Results for Underwater Noise Levels

7.1 SEL contours over the horizontal plane

7.1.1 Port Facility (Stage 1)

During the Q4 season, the negative gradient in the sea's sound-speed profile (Figure 4) will cause waterborne sound to refract downward and thus reflect off the seafloor more frequently in traversing a given distance than it would in an iso-speed profile. As distance increases, this effect will result in SEL being lower during Q4 than during the other three seasons. In order to predict noise levels representative of maximum levels, calculations will be done using the iso-speed (depth-independent) sound-speed profile characteristic of seasons Q1 to Q3. If it should happen that pile driving is conducted during Q4, then the predictions made here will be a little high.

In preparing to run range-dependent PL model AMBO over the plane centred on the Port acoustic datum, the source depth was set at 10.6 m (close to the middle of the water layer), and the receiver depth was set at 3 m. Since a depth of 3 m is in the zone where the negative reflectivity of the sea surface could increase PL (reduce SEL) at frequencies below a few hundred Hertz, modelling has been conducted, using ORCA, along the deepest bearing (298^{o}) for receiver depths from 3 to 21 m to examine the sensitivity of SEL to receiver depth (for a constant seafloor depth at the average depth along this bearing). As the deepest propagation path at the Port was along the dredge channel, the sea floor depth (SFD) would be constant and thus ORCA is an appropriate model for this path. The results were computed for the median rather than the 95% probability level of SELSL (since variation with receiver depth is being examined, rather than absolute values). The results at receiver depths in multiples of 3 m are shown in Figure 11. At a fixed distance of 1000 m (for example), the SEL is 152 dB re μPa^2.s at 3 m depth, increases to a maximum of 157 dB re μPa^2.s as receiver depth passes 11 m, (not shown in Figure 11) decreases to 149 dB re μPa^2.s at 20 m and finally approaches 145 dB re μPa^2.s as the receiver approaches the seafloor (21 m at HAT). Bottom-foraging animals would therefore be subjected to perceived SEL between 2 and 7 dB lower than those that would be predicted for a receiver depth of 3 m. An estimation of increased impact distance at 11m depth has been conducted and is presented in Section 10.1. It can be seen from Figure 11 that the variation with receiver depth is similar to that at 1000 m at other distances, but becomes more pronounced as distance increases.

In order to produce a contour plot of SEL, AMBO has been run along each of the 36 paths from the acoustic datum (using bathymetry during HAT), at the 23 frequencies in third-octave steps from 80 Hz to 12.5 kHz. The resulting contours for a SELSL of 211 dB re μPa^2.s are shown in Figure 12 in Appendix A. As mentioned in Table 10, this SELSL corresponds to the 95% confidence level for a single blow by a 368-kJ hammer on a 1500-mm pile. To cater for the slenderer piles at the Port (from the list in Table 10), the difference in SELSL should be subtracted from the numeral associated with each contour. On bearings from SW to NE of acoustic datum, the contours are approximately circular, indicating that over the frequency band 100 Hz – 12.5 kHz the seafloor depth has little effect on PL, providing the seafloor depth is at least 15 m. For the bearing of 298° (along which the seafloor depth is constant), an ORCA run was conducted and found to give identical results to those of AMBO. At a distance of 1000 m, SEL is close to 150 dB re μPa^2.s at bearings from 200° to 360° and then on from 0° to 40°. South-East of the datum the seafloor becomes very shallow as the shoreline is approached, and the steep side of the channel (mentioned in section 4.6 on mode coupling) causes a peak in SEL. As a result, the 155 dB re μPa^2.s contour is at a greater distance inshore than offshore, and the 150 dB contour extends further on bearings of 70° and 180° than it does on other bearings. This result is due to the shear speed in the seabed. The minimum contour displayed is that for SEL = 145 dB re μPa^2.s; SEL reduces below 145 dB re μPa^2.s rapidly as the shoreline is approached, but those contours are not displayed.

In order to determine the effect of changes in seafloor depth between LAT and HAT, SEL has been computed for five hypothetical cases with constant seafloor depths that varied case-to-case from 4 to 20 m. The GAM depicted in Table 7 was again used, but the source depth was raised to 3 m, since otherwise the results would be confounded by the source lying below the seafloor in some cases. The range of depths was selected to encompass the depths of the profiles shown in Figure 6. The results are shown in Figure 13 in Appendix A. In this figure, seafloor depths are indicated by the numerals in the legend. SEL decreases with increasing distance from datum; however the rate of decrease varies for changes in seafloor depth between 4 and 10 m. At a given distance, SEL is relatively constant for all seafloor depths greater than 6 m, and decreases by 1 to 2 dB as the seafloor depth decreases to 5 m. It is evident that, providing the seafloor depth is at least 6 m (which includes almost all the depths displayed in Figure 6), there will be no significant tidal variation in SEL.

The spectra of SEL have been computed along the 298° bearing (using ORCA) at discrete distances of 1, 10, 100 and 1000 m. The results are shown in Figure 14. The spectra retain the original shape at 1 m to some degree except at the low frequencies (80 and 160 Hz) where the energies reduce more quickly with distance than those at higher frequencies (the phenomenon of low-frequency cut-off in shallow water). Although the changes are small over a distance of 1000 m, high frequencies (~12.5 kHz) also reduce more quickly with distance than those at frequencies of the order of 1000 Hz. The shapes of the spectra indicate that the optimum propagation frequency is between 630 and 2500 Hz.

7.1.2 Humbug barge terminal

Underwater noise propagation was assessed at a receiver depth of 3 m for a range of pile sizes between 600 and 1050 mm and the minimum length of the broadest pile is 30 m. The corresponding fundamental frequency is 84 Hz which lies in the 80-Hz third-octave band. The SEL contours for a single hammer blow on a 1050-mm pile (SELSL = 208 dB re μPa^2.s) are shown in Figure 15. The low values WNW of Humbug are due to the very shallow water.

As was conducted for the Port, ORCA was used to determine the loudest received level at varying depth, along the deepest bearing at the Humbug facility for which the average seafloor depth was 11.7m, Modelling using ORCA assumed the SFD to be constant at its average value. Noise levels along the deepest bearing (270^o) were determined to be 1 dB higher at 9m than at

3m. At the river facilities the assumed sea floor depth would vary. Therefore to determine impact distances, the increase in SEL associated with the depth dependant highest received level along the deepest propagation path, was applied to the SEL computed with AMBO along all bearings to provide a conservative estimate at the facility. An estimation of increased impact distance, adjusted for this increased SEL has been conducted and is presented in Section 10.2.

The SPL radiated by the vibratory hammer (while driving sheet piles) would vary with distance in the same manner as SEL, since bottom reflections contribute to the RMS of the signal. Figure 15 can therefore be regarded as a plot of the SPL contours that would occur for a SPLSL of 208 dB re μPa^2. For an SPLSL of 185 dB re μPa^2, each contour should be reduced by 23 dB.

An additional temporary facility is planned for the Humbug terminal that would entail driving piles of diameter 600 m and length 15 m. These short piles would have a fundamental frequency in the 160-Hz third-octave band. Pile driving for this temporary facility would cause less noise than that from driving permanent 30-m long 1050-mm piles at the Humbug terminal acoustic datum for the following reasons:

(1) the temporary piles have smaller diameters. Although the effect of this on SEL would be offset since they are shorter (the impact energy is not spread into frequencies below 160 Hz that propagate weakly in shallow water), modelling has indicated that the SEL contours from the proposed slender short piles are very close to those for the broad long piles when both are hammered at the same position ("acoustic datum");

(2) the temporary piles would all be hammered in shallower water than the permanent piles;

(3) they would all be further from open water than the permanent piles; and

(4) the sectors of open water they would ensonify (radiate into) are all contained within the sectors that would be ensonified by the permanent piles.

7.1.3 Hornibrook ferry/tug terminal

Underwater noise propagation at a receiver depth of 3 m was assessed for a range of pile sizes between 600 and 1050 mm and their minimum length is 30 m. The corresponding fundamental frequency is 100 Hz which lies in the 100-Hz third-octave band.

As was conducted for the Port, ORCA was used to determine the loudest received level at varying depth, along the deepest bearing at the Hornibrook facility along which the average seafloor depth was 16 m, Modelling using ORCA assumed the SFD to be constant at its average value. Noise levels along the deepest bearing (290^{o}) were determined to be 4.6 dB higher at 12m than at 3m. At the river facilities the assumed sea floor depth would vary. Therefore to determine impact distances, the increase in SEL associated with the depth dependant highest received level along the deepest propagation path, was applied to the SEL computed with AMBO along all bearings to provide a conservative estimate at the facility. An estimation of increased impact distance, adjusted for this increased sea level has been conducted and is presented in Section 10.3.

The acoustic datum selected for the Hornibrook facility is at the southern most point of the tug depot, since that would be in deeper water (10.6 m HAT) than the southernmost point of the ferry terminal (5.4 m HAT). As the source levels for the ferry terminal are not anticipated to be greater than those used in modelling the tug depot, it is considered that modelling for the Hornibrook tug depot is a cautious representation of the ferry terminal. The SEL contours for a single hammer blow on a 1050-mm pile are shown in Figure 16. Simultaneous piling at the Hornibrook ferry and tug facilities would not occur.

7.1.4 Hey River ferry/barge terminal

Underwater noise propagation was assessed at a receiver depth of 3 m for a range of pile sizes between 600 and 1050 mm, and the minimum length of the broadest pile is 30 m. The corresponding fundamental frequency is 84 Hz which lies in the 80-Hz third-octave band. The SEL contours for a single hammer blow on a 1050 mm pile are shown in Figure 17.

As was conducted for the Port ORCA was used to determine the loudest receiver level at varying depth, along the deepest bearing at the Hey River facility, modelling using ORCA assumed the SFD to be constant at its average value (10.6 m). Noise levels along the deepest bearing (40°) were determined to higher by 1.5 dB at 8 m than at 3m. At the river facilities the assumed sea floor depth would vary. Therefore to determine impact distances, the increase in SEL associated with the depth dependant highest received level along the deepest propagation path, was applied to the SEL computed with AMBO along all bearings to provide a conservative estimate at the facility. An estimation of increased impact distance, adjusted for this increased sea level has been conducted and is presented in Section 10.4.

As for Humbug, there would be an additional temporary facility at the Hey River terminal that would require the driving of piles of diameter 600 mm and length 15 m. Modelling has identified that driving these temporary piles would cause no more noise than driving permanent 30-m long 1050-mm piles at the Hey River terminal acoustic datum for the same reasons as apply at the Humbug terminal.

7.2 Peak SPL contours over the horizontal plane

For quasi-iso-speed seawater (i.e. in three of the four seasons), sound waves travel along straight paths. For iso-thermal water, propagation paths are circular arcs with a radius of approximately 90 km. For propagation to distances up to 1 km the rays will bend by an angle of 1 /90 radians = 0.6 degrees, having no effect on the received SPL as, there will be no acoustic shadow zones. The only mechanism by which Peak SPL would not follow spherical spreading plus absorption (SSPA) would be if the sound-speed profile in the seabed had a gradient sufficiently high to cause rays that penetrate the seabed to be refracted (rather than reflected) back to the water layer. Such rays would focus and generate an area (in the range-depth plane) of high SPL known as a caustic. In shallow water, this is possible in principle (Brekhovskikh and Lysanov 1982, page 87), but if it did occur it would show up in the SEL spatial contour plots (Figure 12 and Figure 15 to Figure 17), since the high SPL in a caustic is quasi-independent of frequency (after allowing for absorption). It can be seen from these SEL contour plots that there is no indication of this phenomenon in any of the present scenarios.

In the following results for P-SPL, source and receiver depths are not specified (the model for P-SPL has no dependence on them), but the receiver is assumed to be shallower than the seafloor over the region contoured.

7.2.1 Port Facility (Stage 1)

A contour plot of P-SPL from driving a pile of diameter 1500 mm at the Port site is shown in Figure 18 in Appendix A. The resulting contours are quasi-circular from SSW around (clockwise) to NE, but flatten out parallel to the shoreline from ENE to S.

7.2.2 Humbug barge terminal

A contour plot of P-SPL from the impact hammering of a 1050-mm pipe pile at the Humbug site is shown in Figure 19. The irregularity in the contours to the West corresponds to the topography in very shallow water. The estimated P-SPL from the vibratory hammer would be approximately 35 dB less than from the impact hammer.

7.2.3 Hornibrook ferry/tug terminal

A contour plot of P-SPL from driving a pile of diameter 1050 mm at Hornibrook is shown in Figure 20. The contours show a uniform propagation loss in the arc calculated.

7.2.4 Hey River ferry/barge terminal

A contour plot of P-SPL from driving a pile of diameter 1050 mm at the Hey River terminal is shown in Figure 21. The 180 to 190 dB re μPa^2 contours are circular away from the shoreline.

7.3 Drilling

If required, the Drive-drill-drive method would be used in more challenging ground conditions. If pile driving refusal occurs at an initial toe depth above the target depth, the inside of the pile and remaining substrate to target depth would be drilled. Final re-drive into the open socket can then achieve pile penetration to the target depth.

A typical drill is the Aker Wirth drill with maximum rotation speed of 64 RPM, a fundamental tone with a frequency of 1.07 Hz and several potential overtone frequencies. The overtones would be multiples of the fundamental, with their amplitudes decreasing with frequency. The fundamental and low-order overtones are Very Low Frequencies (VLF) that are infrasonic and inaudible to all animals, as can be seen from the audiograms in Figure 22 in Appendix A, which are discussed in Section 9.1.3.

Two published reports have been sourced of sound signals emitted during the drilling of a socket for a pile: Nedwell *et al*. (2003) and Ward (2012).

(i) Nedwell *et al*: Piles for wind turbines were installed at North Hoyle, 7.5 km offshore from the north coast of Wales. The seafloor depth at LAT varied between 7 and 11 m. The seabed there consists of a 14-m layer of predominantly gravelly sand overlying sandstone. After initial impact hammering, sockets had to be drilled in the sandstone for all of the piles, using a drill head within the 4-m pile. Nedwell measured a spectrum of the noise from drilling inside one pile at a distance of 330 m. At this short range, the Propagation Loss at audio-frequencies may be estimated from an empirical model (Marsh and Schulkin 1962). The result is 20 log (330) - 6

= 44 dB, in which the 6 dB reduction is the appropriate value for the "near-field anomaly" that accounts for contributions by surface and seafloor reflections. For each of the 10 highest peaks (mostly tones) in the spectrum, SPLSL has been obtained by adding 44 dB to the reported SPL. The third-octave bands that contain the frequencies of the 10 loudest peaks, together with their corresponding SPLSLs, are listed in Table 11. Since the loudest peak (at 125 Hz) exceeds the other nine by at least 12 dB, the contribution of the other peaks to the wideband SPL is negligible, and the wideband SPL is thus approximately 156 dB re μPa^2.

(ii) Ward: Piles for the Oyster wave energy converter were installed at the European Marine Energy Centre (EMEC) Wave test site, 800 m offshore from Billia Croo, Orkney, Scotland. The seafloor depth was 12 m. The seafloor there is mainly exposed bedrock with occasional patches of gravely sand overlain with cobbles and boulder. Foundation sockets were drilled using a 4.25-m diameter drill bit. Ward measured a third-octave spectrum of the drill noise at an unspecified distance, and reported results for Source Level (at 1 m) in his Appendix A. The frequencies of the 10 loudest peaks and their SPLSLs are listed in Table 11. According to Ward, “Measurements recorded during the drilling of the socket for Oyster 801 indicated that the total underwater noise levels (defined as the sum of background noise and drilling noise) were 153.8 ± 12.1 dB re 1 µPa at 1 m.” When the 41 band-levels in the spectrum in Ward’s Appendix A (from 10 Hz to 100 kHz) are converted from decibels to μPa^2 and summed, they yield a wideband level of 163 dB re μPa^2, which lies within the spread of data that Ward reported.

Table 11: Characteristics of noise radiated during drilling of pile socket.

Reference	Activity	Seafloor depth (m)	Analysis bandwidth and resolution (Hz)	Frequencies of 10 loudest third-octave bands (Hz)	Estimated SPLSL of loudest bands (dB *re* 1µPa^2 @ 1 m)
Nedwell *et al* 2003, Figure 38	Rock socket drilling; drill head within 4-m pile	7 – 11 LAT	20-100k, 1	25, 125, 160, 250, 315, 400, 500, 630, 800, 1000	135, 156, 134, 144, 124, 141, 132, 131, 129, 128
Ward 2012, Figure 4.2 and Appendix A	Foundation sockets for Oyster wave energy converter, 4.25-m diameter drill bit	12	10-100k, 1/3 octave	125, 315, 400, 500, 1000, 5000, 6300, 8000, 10000, 12500	148, 154, 152, 152, 149, 149, 152, 152, 150, 148

Since the data presented are all at frequencies above 100 Hz, it may be inferred that they apply to the drilling rig rather than the drilling itself. Low-frequency cut-off in the very shallow water would have attenuated signals at lower frequencies.

Since the estimates of wideband SPLSL from examples (i) and (ii) are within 7 dB of each other, it is reasonable to conclude that wideband SPLSL from pile socket drilling would be no more than the higher value of 163 dB re μPa^2.

Since the data reported by Nedwell and Ward did not exhibit high SPL at the infrasonic frequencies radiated by the drill (due to shallow-water low-frequency cut-off), it is reasonable to question whether their data provide representative values for drilling noise from construction of the South-of Embley facilities. The answer to this question is threefold:

i. low-frequency cut-off would also occur at all South-of-Embley facilities,

ii. hearing thresholds of all animals increase as frequency decreases, as can be seen in Figure 22,

iii. the measurements and observations on which Southall's critical SPL and SEL were based generally involved audio frequencies rather than infrasonic frequencies.

It is therefore concluded that impact distance predicted on the basis of the above data would provide reasonable estimates of the actual impact distance.

8.0 Mitigation Options

8.1 Cushions

Before being hammered, a pile has the following objects placed on its top face (listed bottom first): pile cushion (optional), pile cap, hammer cushion, and anvil. For steel piles, pile cushions are used to reduce the noise generated during driving (for other piles, they prevent the pile from being damaged). Materials typically used for cushions include wood, nylon, and micarta. Studies conducted by the Washington State Department of Transportation (Laughlin 2006, 2007) indicate reductions in SPL and SEL with three types of pile cushion as listed in Table 12.

Table 12: Cushion details and expected reductions

Material	Disk thickness (mm)	Number of disks in cushion	Reduction in SPL (dB)	Reduction in SEL (dB)
Plywood	100	3 or 4	11 - 26	11 - 13
Micarta	25	Not reported	7 - 8	6 - 7
Nylon	50	Not reported	4 - 5	6 - 8

A wood cushion should be replaced after a maximum of 1500 blows (Rausche *et al*. 1986). Laughlin (2006) concluded that a wood cushion may last for one pile only, whereas the other materials can be reused on several piles before they need to be changed.

Laughlin (2006) also studied "conbest" (canvas-based laminate) cushions, but his samples had negligible acoustic effect. However, other US transportation departments (Rausche *et al*. 1986, for example) regard conbest to be equivalent to micarta.

Steel cable ring cushions were studied by Nehls *et al*. (2007, page 18). A reduction in SPL of several dB with the first blow was observed, but the reduction decreased to zero after between

10 and 20 blows. SEL was also reduced by 13 dB on the first blow, but the reduction decreased to only 1 or 2 dB after approximately 13 blows.

8.2 Bubble screens

According to ICF Jones and Stokes and Illingworth and Rodkin, Inc (2009), bubble curtains can be highly effective in the right circumstances, but require maintaining a high air fraction in the water close to the pile, which is often impractical - especially when there are significant currents.

According to the results from Vagle (2003), bubble screens reduce wideband P-SPL from pile driving by between 4 and 10 dB.

8.3 Soft Start

Nehls *et al.* (2007) identified that marine mammals may be deterred from pile driving activity by a soft start procedure. A soft start-up involves the force used in piling hammer strikes being progressively increased to alert animals to the commencement of the operations (Bailey *et al.* 2010; Robinson *et al.* 2007). The distance of potential injury to an animal is therefore reduced while deterring animals from the operations outside of this distance.

A soft start is achieved through controlling hammer energy to achieve a reduction in noise levels generated. For example, given the relationship of energy of a noise source to noise levels emitted, a reduction of hammer energy by half would produce an SPL reduction of 3 dB in each of SPL, SEL and P-SPL.

Bailey *et al.* (2010) described a soft start procedure which commenced with reduced hammer energy of 63kJ from a maximum energy of 510kJ or approximately 1/8th of maximum energy. This would have an effect of reducing the noise emission by 9 dB at the initiation of piling. Robinson *et al.* (2007) described a soft start procedure which commenced with a reduced hammer energy of 80kJ increasing to 800kJ or 1/10th of the energy. This would have the effect of reducing noise emission by 10 dB at the initiation of piling.

8.4 Acoustic Mitigation Devices (AMD)

The acoustic deterrents mentioned by Nehls are also known as Acoustic Mitigation Devices (AMD). It appears that commercially available AMDs emit signals in the frequency band from 10 kHz to 40 kHz (Kastelein *et al*. 2010), and thus target mammals, but not turtles or sawfish.

9.0 Critical Sound levels for the animal groups

The critical levels will be determined for each animal group. In chapter 10 these critical levels will be applied to each facility in order to produce impact distances.

9.1 Cetaceans

According to Southall *et al*. (2007):

- We distinguished two basic sound types: (1) pulse and (2) nonpulse.

- The pulse/nonpulse distinction is important because pulses generally have a different potential to cause physical effects, particularly on hearing.

In the present report, noise from drilling and vibratory pile drivers will be treated as non-pulse signals.

Southall distinguishes between “low-frequency” (LF), “mid-frequency” (MF) and “high-frequency” (HF) cetaceans, on the basis of the frequency band of the animal’s audiogram. The three bandwidths are LF = 7 Hz – 22 kHz; MF = 150 Hz – 160 kHz; and HF = 200 Hz – 180 kHz (op. cit., page 430). Baleen whales are generally LF, and toothed cetaceans are either MF or HF. All dolphins are toothed. Of the three cetacean species considered (Table 4) the baleen whale is LF and the two dolphin species are MF. Audiograms for the specific species listed are unavailable; those of the (MF) bottlenose dolphin and baleen whales are shown in Figure 22.

9.1.1 LF Cetacean Behaviour disturbance

Critical values for behaviour disturbance are expressed in terms of SPL only (Southall *et al*. page 452).

For LF cetaceans exposed to multiple pulses, a summary of behaviour disturbance is presented in Table 7 of Southall et al (page 454). This is a table of Behaviour Response score versus received SPL, showing in each cell the applicable count of individuals/groups that have been reported. It includes reports by McCauley *et al*. (1998, 2000) in the Australian region. It can be seen from the table that there are several reports of SPLs between 115 and 175 dB re μPa^2 causing a Response score of 6 (to 81 individuals or groups of cetaceans), and a report of an SPL of 155 dB re μPa^2 causing a Response score of 7 (to one group) [although the table refers to SPL bins that are 10 dB wide, these bins are referred to here by their midpoints]. It is reasonable to conclude that an SPL of 165 dB re μPa^2 is unlikely to cause a Response score of 7 or more and is thus suitable as the critical value. It is unnecessary to make a correction from the spectrum of the airgun to that of pile driving over the LF band, since this band contains virtually all the energy of both spectra.

For LF cetaceans exposed to non-pulse signals, a summary of behaviour disturbance is presented in Table 15 of Southall *et al*. (page 463). There are several reports of SPLs between 95 and 145 dB re μPa^2 causing a Response score of 6 (to 47 individuals or groups of cetaceans), and one report of SPLs of 135 - 145 dB re μPa^2 causing a Response score of 7 (to four individuals or groups). It is reasonable to conclude that an SPL of 135 dB re μPa^2 is unlikely to cause a Response score of 7 or more, and is thus suitable as the critical value.

9.1.2 MF Cetacean Behaviour Disturbance

For MF cetaceans exposed to multiple pulses, Southall’s Table 9 is sparsely populated (the total count is 16, compared with 197 in his table 7 for LF). For SPL of 175 dB re μPa^2, there are 8 counts, all of which resulted in acceptable behaviour disturbance (response score ≤ 6). Since the sound sources used were “numerous sounds including pulse sequences” in laboratory conditions, it is considered unnecessary to correct from the spectra of the sources used to that of pile driving. The other results shown in Southall’s Table 9 are for SPL of no more than around

145 dB re μPa^2. It is reasonable to conclude that an SPL of 175 dB re μPa^2 is a suitable critical value for MF cetaceans. This should be increased to 177 dB re μPa^2.s to convert from MF to wideband spectra. The corresponding SEL per blow is 164 dB re μPa^2.s [Eq.(2)].

For MF cetaceans exposed to non-pulse signals, a summary of behaviour disturbance is presented in Table 17 of Southall *et al*. (page 466). There are reports of SPLs between 95 and 195 dB re μPa^2 causing a Response score of 8 (to 21 individuals or groups of cetaceans), and reports of SPLs of 115 - 175 dB re μPa^2 causing a Response score of 6 (to 11 individuals or groups). It is reasonable to conclude that an SPL of 175 dB re μPa^2 is a suitable critical value for MF cetaceans. This should be increased to 177 dB re μPa^2.s to convert from MF to wideband spectra.

On reviewing the four critical SPLs for LF and MF cetaceans for both multi-pulse and non-pulse signals, it seems anomalous that for LF cetaceans the non-pulse value (135 dB re μPa^2) is 30 dB less than the multi-pulse value (165 dB re μPa^2), whereas for MF cetaceans the corresponding values are the same (177 dB re μPa^2). It is possible that this anomaly is an artefact of the attempt to draw quantitative conclusions from sparse data. Nevertheless these results represent the state of the art, and no alternative procedure appears to be available.

9.1.3 Cetacean Injury

Criteria for injury due to multiple pulses are expressed in terms of both P-SPL and cumulative SEL (Southall *et al*. page 443). The critical P-SPL for cetaceans is 230 dB re μPa^2 (Southall op. cit.).

The critical cumulative SEL for injury proposed for individual cetaceans exposed to multiple pulses within a 24-hour period is 198 re μPa^2.s, weighted by the animal's average hearing threshold (Southall op. cit.). Since the LF bandwidth contains virtually all the energy of the pile-driving noise spectrum (80 Hz – 12.5 kHz), the audiogram-weighting correction will be zero for baleen whales. The MF band excludes frequencies below 150 Hz, and thus pile-driving noise at those frequencies would be inaudible to dolphins. If the pile-driving noise were recomputed by omitting frequencies below 150 Hz, it would be around 2 dB lower than the wideband levels shown in Figure 12.

For non-pulse signals the critical cumulative SEL is 215 dB re μPa^2.s. Over 0.4 hours (1440 s), the SELSL of the vibratory hammer would be SPLSL + 10 log (duration) = 185 + 10 log (1440) = 217 dB re μPa^2.s. For drilling, the SELSL over 0.4 hours would be approximately 163 + 10 log (1440) = 195 dB re μPa^2.s.

9.2 Dugong

An audiogram for a dugong is unavailable and has been assumed to be similar to that of its sirenian relative, the West Indian Manatee (Gerstein *et al*. 1999). It can be seen from Figure 22 that over the frequency band of pile-driving noise (80 Hz – 12.5 kHz) this audiogram is similar to the dolphin, a MF cetacean. The dugong's cruising speed of 10 km/hour is not sufficiently different from that of the dolphin (8 km/hour) to necessitate a separate analysis. For the purposes of this report, the dugong will therefore be treated as equivalent to an MF cetacean.

9.3 Turtle

A typical turtle audiogram (adapted from Tech Environmental, Inc, 2006, page 23) is shown by the green curve in Figure 22. Over the band of intense pile-driving noise, the turtle hearing threshold is at least 15 dB higher than the baleen whale. It can be seen that the hearing bandwidth for turtles is relatively narrow, from 50 Hz to 1000 Hz with maximum sensitivity around 200 Hz.

9.3.1 Turtle Behaviour Disturbance

The conclusion drawn by Southall *et al*, that cetacean behaviour disturbance is determined by SPL alone, is assumed here to also apply to turtles.

Two methods are adopted here for estimating the critical SPL value for the turtle for multi-pulse signals. The first is to compare its audiogram with that of a cetacean, and the second is to use reported data (there are no reported data for non-pulse signals).

Audiogram method: Using the results derived in section 9.1.1, the critical SPL for multiple pulses may therefore be estimated at 165 + 15 = 180 dB re μPa^2.

Data method: According to McCauley *et al*. (2000), trials have shown that when an airgun SPL exceeded 166 dB re μPa^2 the turtles noticeably increased their swimming activity compared to non airgun operation periods. When SPL exceeded 175 dB re μPa^2 their behaviour became more erratic, possibly indicating the turtles were in an agitated state. It is reasonable to conclude that the critical SPL is 170 dB re μPa^2 for multiple pulses, which is 10 dB less than the result from the audiogram method. Their average of 175 dB re μPa^2 will be used as the critical value. The corresponding SEL per blow is 162 dB re $\mu Pa^2.s$ [Eq.(2)].

For non-pulse signals, the audiogram method yields a critical SPL of 135 + 15 = 150 dB re μPa^2.

9.3.2 Turtle Injury

As was done for cetaceans, critical values for injury due to multiple pulses are expressed in terms of cumulative SEL. No impact distance would be required at any facility on the basis of P-SPL. Since there are no reported data on permanent or temporary threshold shifts in turtles, the only method available is to compare audiograms. Using the results derived in section 9.1.3, the critical cumulative SEL for multiple pulses is estimated at 198 + 15 = 213 dB re $\mu Pa^2.s$. A turtle departing at 2 km/hour is expected to be exposed to intense noise for approximately 1 hour, and would thus hear 1315 /12 = 110 blows. The critical SEL per blow would be 213 – 10 log(110) = 193 dB re $\mu Pa^2.s$.

For non-pulse signals the critical cumulative SEL is 215 + 15 = 230 dB re $\mu Pa^2.s$.

9.4 Sawfish

Since sawfish are rays, it is assumed that their hearing response is similar to that of the Yellow stingray (the only ray audiogram found), which is shown by the magenta curve in Figure 22 (adapted from Casper 2006, page 29). Over the bandwidth of intense pile-driving noise the sawfish's hearing threshold is at least 50 dB higher than the baleen whale's. It can be seen that the hearing bandwidth for sawfish is relatively narrow, from 50 Hz to 1000 Hz with maximum sensitivity around 200 Hz.

9.4.1 Sawfish Behaviour Disturbance

As was done for turtles, it is assumed that disturbance of sawfish behaviour is also determined by SPL alone. Since no data on disturbance to sawfish or any rays by loud sounds appears to be available, it will be assumed that the critical SPL for disturbance will exceed that of the baleen whale by the difference in their audiograms. For multi-pulses the critical SPL is therefore 165 + 50 = 215 dB re μPa^2, and the corresponding SEL per blow is 202 dB re $\mu Pa^2.s$ [Eq.(2)]. For non-pulse signals the critical SPL is 135 + 50 = 185 dB re μPa^2.

9.4.2 Sawfish Injury

As was done for cetaceans, critical values for injury to sawfish due to multiple pulses are expressed in terms of cumulative SEL. Again, no impact distance would be required at any facility on the basis of P-SPL. Data on injury to sawfish or any rays by loud sounds appear to be unavailable. It is reasonable to assume that the critical cumulative SEL for injury (permanent or temporary threshold shift) will be 50 dB higher than the baleen whale. The critical cumulative SEL for sawfish is therefore assumed to be 198 + 50 = 248 dB re $\mu Pa^2.s$. A sawfish departing at 1 km/hour is expected to be exposed to intense pile-driving noise for approximately 2 hours, and would thus hear 220 blows. The critical SEL for a single blow would be 248 – 10 log(220) = 225 dB re $\mu Pa^2.s$.

For non-pulse signals the critical cumulative SEL is 215 + 50 = 265 dB re $\mu Pa^2.s$.

9.5 Speartooth Shark

No audiogram was available for the Speartooth Shark. An audiogram of a Nurse Shark is shown by the turquoise curve in Figure 22 (adapted from Casper 2006). Over the bandwidth of intense pile-driving noise the shark's hearing threshold is at least 45 dB higher than the baleen whale's. Since the shark's hearing threshold is only 4 to 6 dB less than the stingray's the results for these two groups are expected to be similar.

9.5.1 Shark Behaviour Disturbance

It is assumed that the critical SPL for disturbance will exceed that of the baleen whale by the difference in their average hearing thresholds. For multi-pulses the critical SPL is therefore 165 + 45 = 210 dB re μPa^2, and the corresponding SEL per blow is 197 dB re $\mu Pa^2.s$ [Eq.(2)]. For non-pulse signals the critical SPL is 135 + 45 = 180 dB re μPa^2.

9.5.2 Shark Injury

It is assumed that the critical cumulative SEL for injury (permanent or temporary threshold shift) to a shark will be 45 dB higher than for the baleen whale. The critical cumulative SELs for a shark are therefore 243 and 260 dB re $\mu Pa^2.s$ for multi-pulse and non-pulse signals respectively. A shark departing at 8 km/hour is expected to be exposed to intense pile-driving noise for approximately 0.3 hours, and would hear 30 blows. The critical SELs for a single blow would be 228 and 245 dB re $\mu Pa^2.s$ for the respective signal types.

9.6 Crocodile

Underwater noise is not identified as having a potential impact on Estuarine Crocodiles (Leach *et al.* 2009) nor is it identified as a threat to the species in the DSEWPaC Species Profile and Threats (SPRAT) database (DSEWPaC 2012). Crocodiles are known to occur within the vicinity of the marine facilities within the Embley River, where similar construction and operational activities have been conducted. Similarly, the species would be expected to continue utilising environments surrounding the Project marine facilities.

9.7 Summary of critical disturbance SPLs for the animal groups

The critical disturbance SPL values for pile-driving, as derived in sections 9.1 - 9.6, are summarised in Table 13. In the context of the present report, non-pulse signals refer to vibratory pile driving, and drilling.

Table 13: Behaviour disturbance - critical values for SPL

Signal type:	Multiple pulse	Non-pulse
LF Cetacean	165	135
MF Cetacean & Dugong	177	177
Turtle	175	150
Sawfish	215	185
Shark	210	180

10.0 Recommended Impact Distances

The bulk of this chapter presents disturbance-based impact distances for marine mammals (whales, dolphins and dugong), turtle, sawfish, and the shark. The final section examines how impact based on injury criteria compare with impact distance based on behaviour disturbance.

For each facility the results obtained for impact distance are listed in the corresponding Table in the sub-sections to follow. Also listed are the estimated impact distances that would apply if a thick micarta pile cushion were utilised (6 dB reduction) on the broadest pile. The corresponding predictions for a thick wood pile cushion are listed in the final column; the reduction is much greater, approximately 12 dB.

The SEL model described in Chapter 4 computed SEL and used to determine SPL at ranges from 5 m outwards in steps of 5 m. The following method was then utilised to determine the impact distance:

(1) If the Critical Value of SPL (CV) exceeded SPLSL, then impact distance < 1 m and was estimated using spherical spreading.

(2) If CV exceeded the value of SPL at 5 m, then impact distance < 5 m and was estimated using logarithmic interpolation between 1 and 5 m.

(3) If CV was less than SPL(5) then impact distance > 5 m and was estimated by linear interpolation between the two ranges between which the difference SPL – CV changed from positive to negative,

This procedure was likewise followed for P-SPL..

For the river facilities, impact distance is expected to be slightly smaller during LAT than during HAT. Impact distance was therefore determined at HAT, providing a conservative assessment of impact distance.

The Speartooth Shark is considered unlikely to occur at the Port and hence impact distances for this species at the Port were not calculated. The Hey and Embley Rivers do not present potential habitat for the LF Cetacean, and hence impact distances for LF Cetaceans are not calculated for the river facilities. The other four animal groups will be referred to as “river-compatible” groups.

10.1 Port Facility (Stage 1)

The Port Facility (Stage 1) would require the largest impact distances, both because the broadest piles are being driven there, and because propagation loss in the vicinity of the port would be no more than (and generally less than) at the river facilities, due to the deeper water. The same predicted impact distances are obtained whether the HAT or LAT seafloor depths are used.

The number of blows required at the port facility would depend on the resistance of the stratigraphy to pile driving, and hence the amount of drilling required. Once the stratigraphy is drilled the piles experience less resistance and therefore require less driving to reach the required depth. If minimal drilling is required then a maximum of approximately 98,600 blows would be struck over a period of 75 days, giving a daily average of 1,315 blows, which is equivalent to 110 blows per hour (33 s /blow). Alternatively if maximum drilling is required then the minimum number of blows would be 72,600 over 180 days, or 403 blows per day. In the minimal drilling scenario without use of a soft start procedure, a whale departing at 5 km/hour is expected to be exposed to intense noise for approximately 0.4 hours, and would thus hear $0.4 \times 1315 / 12 = 44$ blows. The critical SEL per blow would be $198 - 10 \log(44) = 182$ dB re $\mu Pa^2.s$. A dolphin departing at 8 km/hour would hear around 28 blows (without use of a soft start procedure), and impact distance would be somewhat smaller.

For the LF cetacean, since an SPL of 165 dB re μPa^2 corresponds to a pile-driving SEL of 152 dB re $\mu Pa^2.s$ [Eq.(2)], it can be seen from Figure 12 that the Port impact distance for the broad 1500-mm pile at a receiver depth of 3m would be approximately 970 m along a bearing of approximately 68^o and would extend to the shoreline in directions between ESE and S. For the MF cetacean, the critical SEL is 164 dB re $\mu Pa^2.s$ and impact distance (without mitigation) for the broad pile would be approximately 270 m in all directions for a receiver depth of 3m. For the turtle, the critical SEL is 162 dB re $\mu Pa^2.s$ and impact distance (without mitigation) for hammering a broad pile would be approximately 310 m in all directions for a receiver depth of 3m. For sawfish, the required impact distance during the hammering of a broad pile would be less than 10 m for a receiver depth of 3m.

As identified in Section 7.1.1 received sound levels along the dredge channel (bearing of 298^o) at a depth of 11 m are predicted to be 5 dB higher than at a depth of 3 m. As such, impact distances have been determined along this bearing adjusting for the increased received level. Impact distance (without mitigation) during the hammering of a broad pile for the LF cetacean would increase to 1,330m along this bearing. Impact distance during the hammering of a broad pile (without mitigation) for the MF cetacean would increase to 400 m. For the turtle impact distance (without mitigation) during the hammering of a broad pile would increase to 470 m. For sawfish, the required impact distance during the hammering of a broad pile would remain less than 10 m, Impact distances adjusted for the highest received levels at the Port are presented in Table 14 as the maximum impact distances for the animal groups and pile types.

The results shown in Table 14 for the two mitigation options are applicable to the broad pile (1500 mm); impact distances for the more slender piles would be smaller if mitigated.

For drilling (SPLSL = 163 dB re μPa^2) the impact distances are also listed in Table 14, along the bearing of 298^o. For the LF cetacean the critical SPL is 135 dB re 1 μPa^2, a difference of 28 dB. For such small differences, impact distance would be less than 100 m. The impact distance for LF cetaceans is estimated to be 30 m. For the turtle (critical SPL = 150 dB re re μPa^2) the corresponding impact distance is approximately less than 10m. Since the critical SPL for the MF cetacean, sawfish and shark all exceed SPLSL, impact distance for each of these groups would be less than 1 m.

10.1.1 Cumulative impact of simultaneous piling

Given the worst case scenario of:

- 1 x 25t rig working on a 1500mm pile; and
- 2 x 16t rigs working on a 1050mm pile.

There is a potential for increase of sound pressure level (rms) of 2.8 dB over that from the 25t rig at any position equidistant from all three. Based on this potential change, the behaviour disturbance impact distances have been calculated based upon the worst-case simultaneous operation of all three pile rigs and is also shown in Table 14 along the bearing of 298^o.

If there are two 16t rigs working simultaneously then SPL will increase by 3 dB over that from one of the 16t rigs at any equidistant position. If the 25t rig and one 16t rig are working simultaneously then the SPL at any equidistant position will be 1.6 dB over that from the 25t rig.

Impact distances for injury impacts are small (distance of 3 m for peak SPL and 31m for sound exposure). The proposed piling rigs cannot operate any closer than 150m due to the size of the barge and spread on the anchors. As the rigs are proposed to operate with a minimum 150m separation distance, impacts from simultaneous operation of all three rigs cannot cause any significant increase in injury over that which may be caused by single-rig pile driving.

Table 14: Disturbance-based impact distances (metres) from the Port

Animal group	Drilling	Single rig driving							Triple rig driving
		Driving unmitigated					Driving 1500 mitigated		Driving unmitigated
		1500	1200	1050	750	356	TMPC	TWPC	1500 plus two 1050
LF Cetacean	30	1330	1210	930	790	570	700	400	1580
MF Cetacean & dugong	<1	400	360	270	230	170	210	130	500
Turtle	<10	470	430	350	280	210	250	150	630
Sawfish	<1	<10	<10	<10	<10	<10	<10	<10	<10

Note: Impact distance determined from the acoustic datum and along the deepest bearing of 298^{o} (dredge channel)

TMPC = Thick micarta pile cushion, TWPC = Thick wood pile cushion.

10.2 Humbug barge terminal

For the driving of pipe piles at Humbug the Source Levels are less than most of the Port facility piles (SELSL is 206 dB re $\mu Pa^2.s$), and this is reflected in smaller impact distances. As identified in Section 7.1.2 received sound levels were predicted to be higher by 1 dB at 9m than at 3m depth along the deepest modelled propagation path. As such impact distances have been adjusted along all bearings to account for the predicted increased received level at depth. These conservative impact distances are listed in Table 15.

For the vibratory driving of sheet piles (non-pulse signal) at Humbug, SPLSL is 185 dB re μPa^2. The results for impact distance are listed in Table 15 (in the column headed ‘Sheet’).

Table 15: Disturbance-based impact distances (metres) from the Humbug

Animal group	Drilling	Driving unmitigated					Driving 1050 mitigated	
		Sheet	600	750	900	1050	TMPC	TWPC
MF Cetacean & Dugong	<1	<10	130	140	160	170	80	40
Turtle	<10	50	160	180	200	210	100	50
Sawfish	<1	<10	<10	<10	<10	<10	<10	<1
Shark	<1	<10	<10	<10	<10	<10	<10	<10

Note: Impact distance determined from the acoustic datum.

The impact distances here have their maximum values in the westerly direction.

10.3 Hornibrook ferry/tug terminal

At Hornibrook the pile driving Source Level is 206 dB re $\mu Pa^2.s$. As identified in Section 7.1.3 received sound levels were predicted to be higher by 4.6 dB at 12 m than at 3m depth along the deepest modelled propagation path. As such impact distances have been adjusted along all bearings to account for the predicted increased received level at depth. These conservative impact distances are listed in Table 16.

Table 16: Disturbance-based impact distances (metres) from the Hornibrook

Animal group	Drilling	Driving unmitigated				Driving 1050 mitigated	
		600	750	900	1050	TMPC	TWPC
MF Cetacean & Dugong	<1	190	210	230	250	100	60
Turtle	<10	240	280	310	340	150	70
Sawfish	<1	<10	<10	<10	<10	<10	<1
Shark	<1	<10	<10	<10	<10	<10	<10

Note: Impact distance determined from the acoustic datum.

The impact distances here have their maximum values in the SE to SW directions.

10.4 Hey River ferry/barge terminal

At Hey River the pile driving Source Level is 206 dB re μPa^2.s. As identified in Section 7.1.3 received sound levels were predicted to be higher by 4.6 dB at 12 m than at 3m depth along the deepest modelled propagation path. As such impact distances have been adjusted along all bearings to account for the predicted increased received level at depth. These conservative impact distances are listed in Table 17. Results for the vibratory driving of sheet piles and drilling are also shown.

Table 17: Disturbance-based impact distances (metres) from the Hey River

Animal group	Drilling	Driving unmitigated					Driving 1050 mitigated	
		Sheet	600	750	900	1050	TMPC	TWPC
MF Cetacean & Dugong	<1	<10	300	330	360	380	200	90
Turtle	<10	110	370	400	440	470	250	120
Sawfish	<1	<10	<10	<10	<10	<10	<10	<1
Shark	<1	<10	<10	<10	<10	<10	<10	<10

Note: Impact distance determined from the acoustic datum.

The impact distances here have their maximum values in the Northerly and Southerly directions.

10.5 Navigation Aids

Separate SEL contour diagrams have not been produced for the Navigation Aids at 3m depth. SELSL here is 207 dB re μPa^2.s (as it is for the 1050-mm piles at The Port), and the river depths at HAT range from 9 to 15 m. Since the river floor topography is comparatively smooth, the SEL results for the Port have been applied to all three. Given the range of depths of the navigation aids, received sound levels were predicted to increase by between 0 to 4 dB at the immediate vicinity of the pile. The worst-case received level increase was assumed to apply at all navigation aids. As such impact distances have been adjusted along all bearings, to account for the predicted increased received level at depth.

For drilling, the impact distances are assumed to be the same as at the Port facility. These conservative results are listed in Table 18.

Table 18: Disturbance-based impact distances (metres) from the Navigation Aids

Animal group	Drilling	Driving unmitigated	Driving mitigated	
		1050	TMPC	TWPC
MF Cetacean & Dugong	<1	280	150	60
Turtle	<10	360	170	70
Sawfish	<1	<10	<10	<1
Shark	<1	<10	<10	<10

10.6 Injury-based impact distance comparison

For assessing injury, the relevant parameters are P-SPL and SEL. P-SPL is assumed to follow spherical spreading, The critical P-SPL given by Southall et al is 230 dB re μPa^2, and the maximum impact distances is less than 10 m (4 m), which occurs for the broadest pile at the Port (P-SPLSL = 242 dB re μPa^2). A check has been undertaken to determine whether, for any animal group, the impact distance based on injury exceeds the distance based on disturbance. For injury due to pile-driving (multi-pulse) signals, impact distance is where SEL per blow equals Critical cumulative SEL – 10 log (Number of blows).

The critical cumulative SEL for injury to the individual animal groups were derived in sections 9.1.3 (cetacean), 9.3.2 (turtle), 9.4.2 (sawfish), and 9.5.2 (shark) and are summarised in Table 19. The hammer rate is assumed to be 110 blows /hour.

Table 19: Critical cumulative injury values for multiple-pulse signals.

Animal group	Duration (hours) *	Number of blows	Critical cumulative SEL (dB re μPa^2.s)	Critical SEL per blow (dB re μPa^2.s)
LF Cetacean	0.4	44	198	182
MF Cetacean & Dugong	0.25	27	200	186
Turtle	1	110	213	193
Sawfish	2	220	248	225
Shark	0.25	27	243	228

* Duration required to travel 2km

For mobile marine animals, avoidance behaviour is well established in the peer reviewed literature as the common response to underwater noise when that noise reaches a certain threshold (Janik and Thompson, 1996; Nowacek *et al*. 2001; Ng and Leung 2003; Hodgson and Marsh 2007; DeRuiter and Doukara 2012; Southall *et al*. 2007). As an animal moves away from the sound source, the perceived SEL per blow would gradually decrease with each succeeding blow. The rate at which cumulative SEL (as perceived by an individual animal) increases with time would decrease until the animal reaches a distance where it no longer seeks to avoid the sound source. In estimating injury, although it is necessary to calculate cumulative SEL, the gradual decrease will not be taken into account. The cumulative SEL will be calculated on the assumption that the animal remains at the impact distance that produces a disturbance Response score of 6, for the duration required for it to travel 2 km. This will over-estimate somewhat the actual cumulative SEL likely to be perceived by an animal. The recommended impact distance will be calculated to match the cumulative SEL to the critical value for any animal. This aspect will be quantified for each of the animal groups.

If each animal were positioned at their disturbance distance, the SEL they would perceive for each hammer blow would be numerically 13 dB less than the multi-pulse SPL values listed in Table 13. It can be seen that these SEL values are all 20 to 30 dB less than the corresponding values for critical injury SEL per blow listed in Table 19.

To assess injury due to drilling, Eq. (5) is used with T given the group-specific durations discussed in Chapter 9, and SPL = SPL (critical), the non-pulse values listed in Table 13. The parameters for each animal group are listed in Table 20, and the cumulative SEL are listed in the final column. By comparing these cumulative SEL values with the critical non-pulse values in Table 19 it can be seen that the former are smaller than the latter, by large margins for most groups. Except for the MF Cetacean & Dugong, the durations would have to be increased by a factor of at least 100 before the SEL injury criterion would result in a larger impact distance than the disturbance criterion. A similar result is obtained when the analysis is repeated for vibratory-hammer noise. It is concluded that in the context of the present report impact distance is larger for behaviour disturbance than injury.

Table 20: Critical cumulative disturbance and injury values for non-pulse signals

Animal group	Duration T (s)	Critical disturbance nonpulse SPL (dB re μPa^2)	Disturbance cumulative SEL* (dB re $\mu Pa^2.s$)	Critical injury Non-pulse cumulative SEL (dB re $\mu Pa^2.s$)
LF cetacean	1440	135	167	215
MF cetacean & dugong	900	177	207	215
Turtle	3600	150	186	230
Sawfish	7200	185	224	265
Shark	900	180	210	260

* = SPL(critical disturbance nonpulse) + 10 log T. Example : 135+10log(1440)=167

Appendix A - Figures

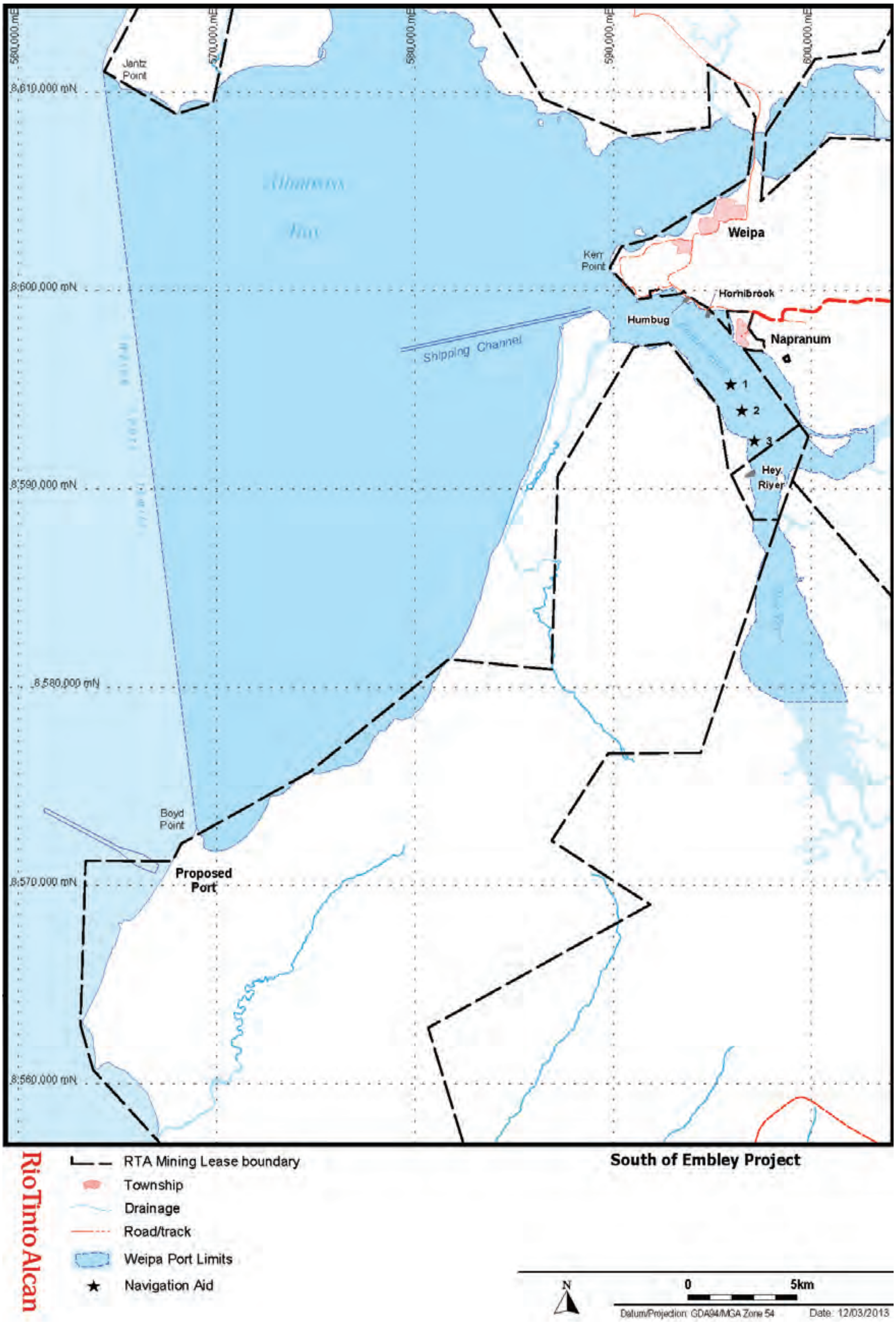
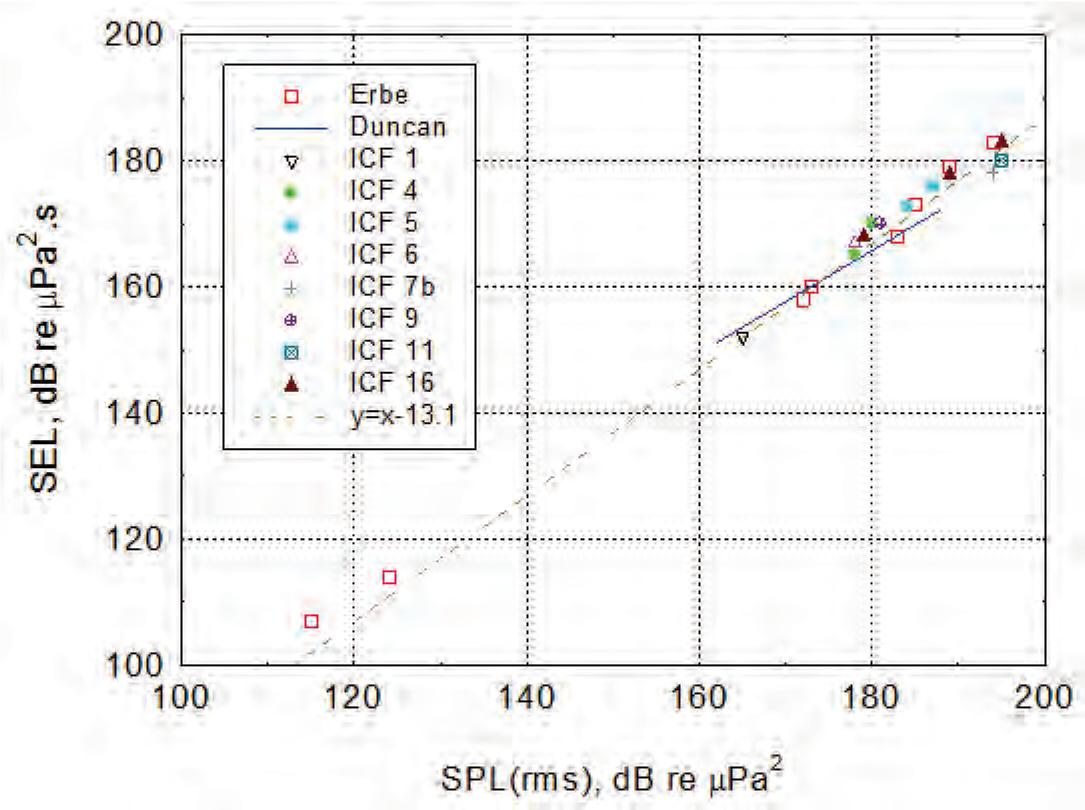


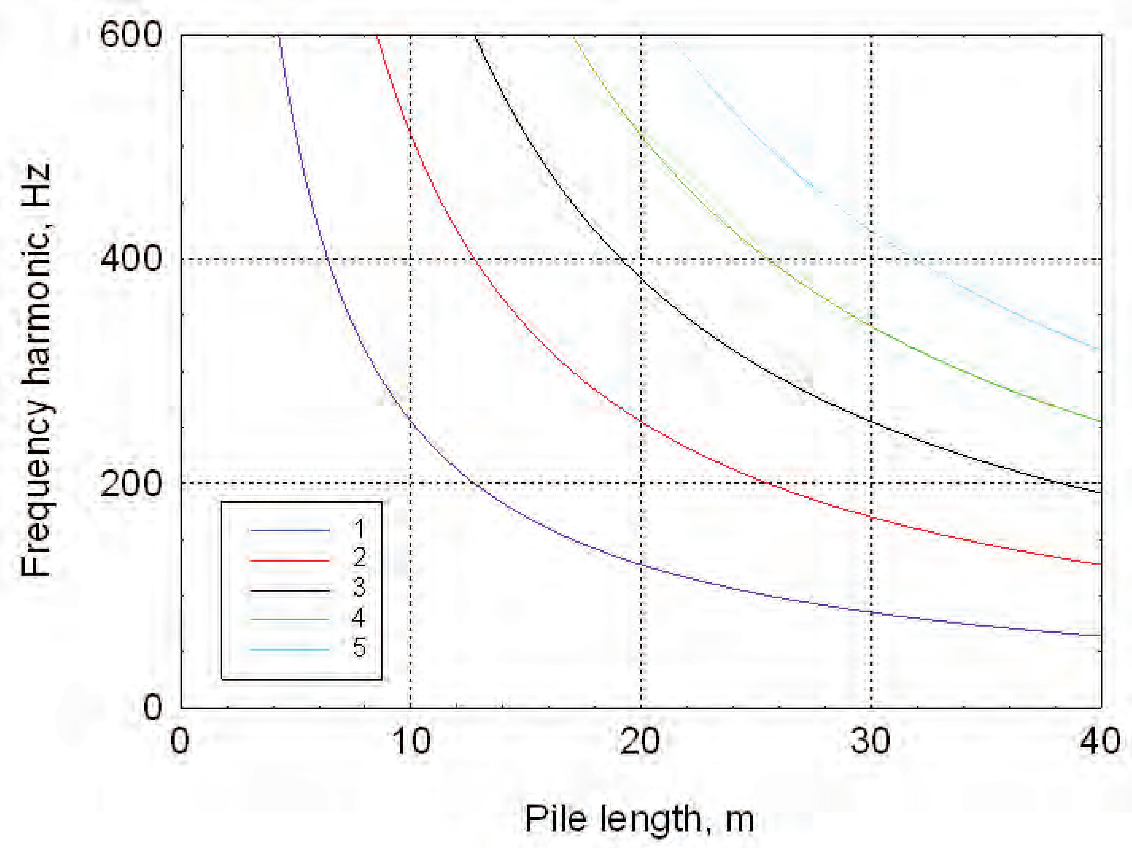
Figure 1: Locations of the marine facilities



Note: Data sources are indicated in the legend.

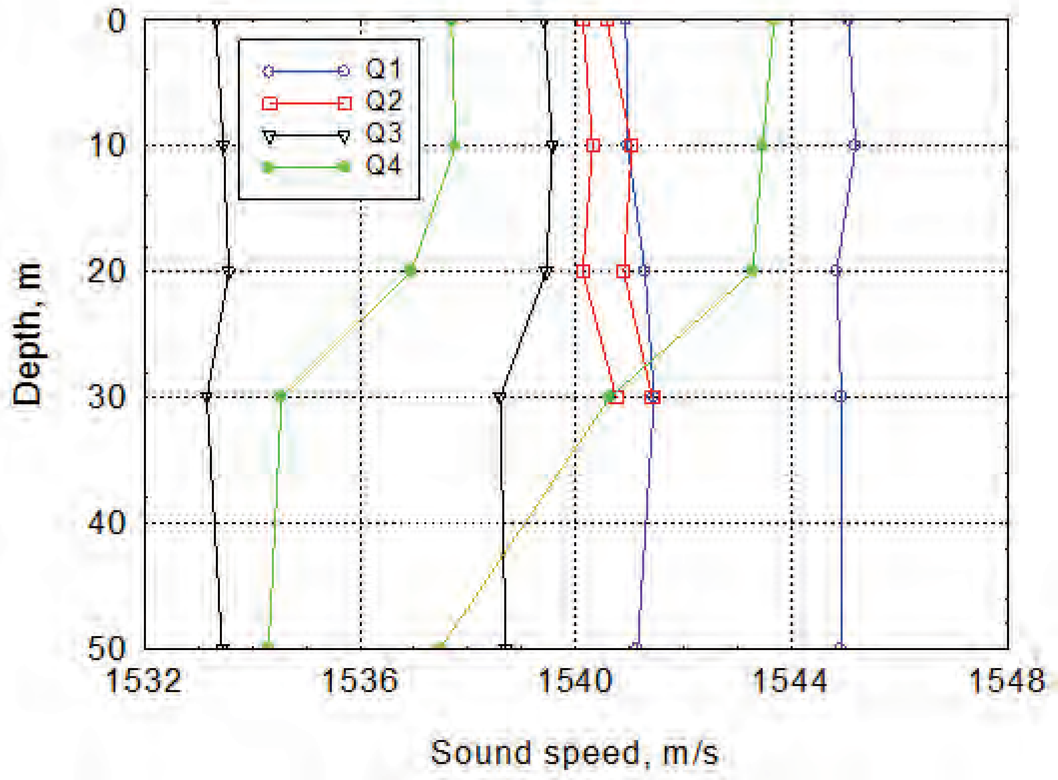
For ICF 1 the hammer included a wood cushion block

Figure 2: Results for SEL of a single hammer blow, vs. the corresponding SPL.



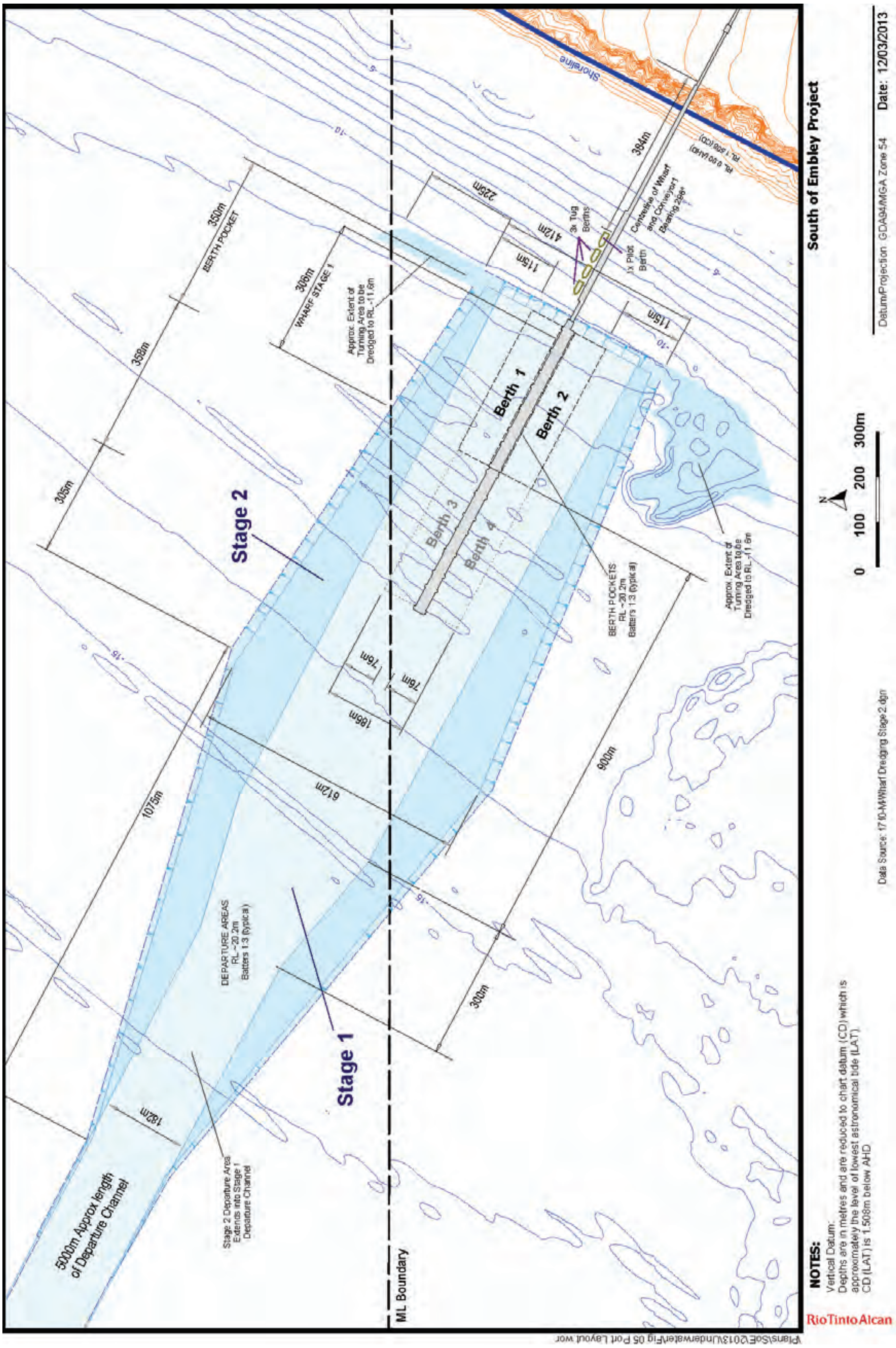
KEY: Blue – fundamental (1st harmonic);, red – second harmonic;, black – third harmonic;, green – fourth harmonic;, turquoise – fifth harmonic.

Figure 3: Longitudinal resonance harmonic frequencies of an unclamped slender steel cylinder (hollow or solid) as function of cylinder length.



KEY to seasons: Q1 is Jan – Mar;, Q2 is Apr – Jun;, Q3 is Jul –- Sep;, Q4 is Oct – Dec.

Figure 4: Seawater sound-speed profiles in the five-degree square near Weipa.



Note: Shows location of proposed wharf and jetty in stages

Figure 5: Contours of offshore bathymetry around the proposed Port

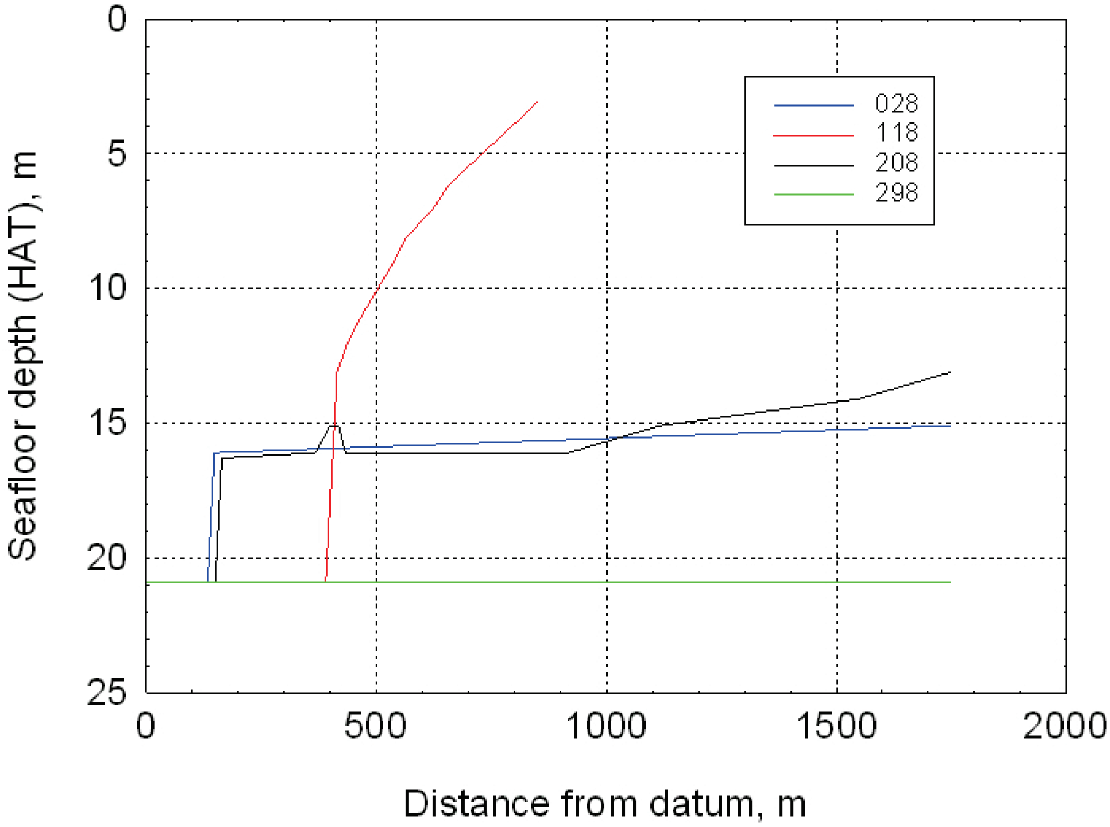


Figure 6: Coarse-scale bathymetry during HAT along four bearings (028°, 118°, 208° and 298°) from acoustic datum at the proposed Port

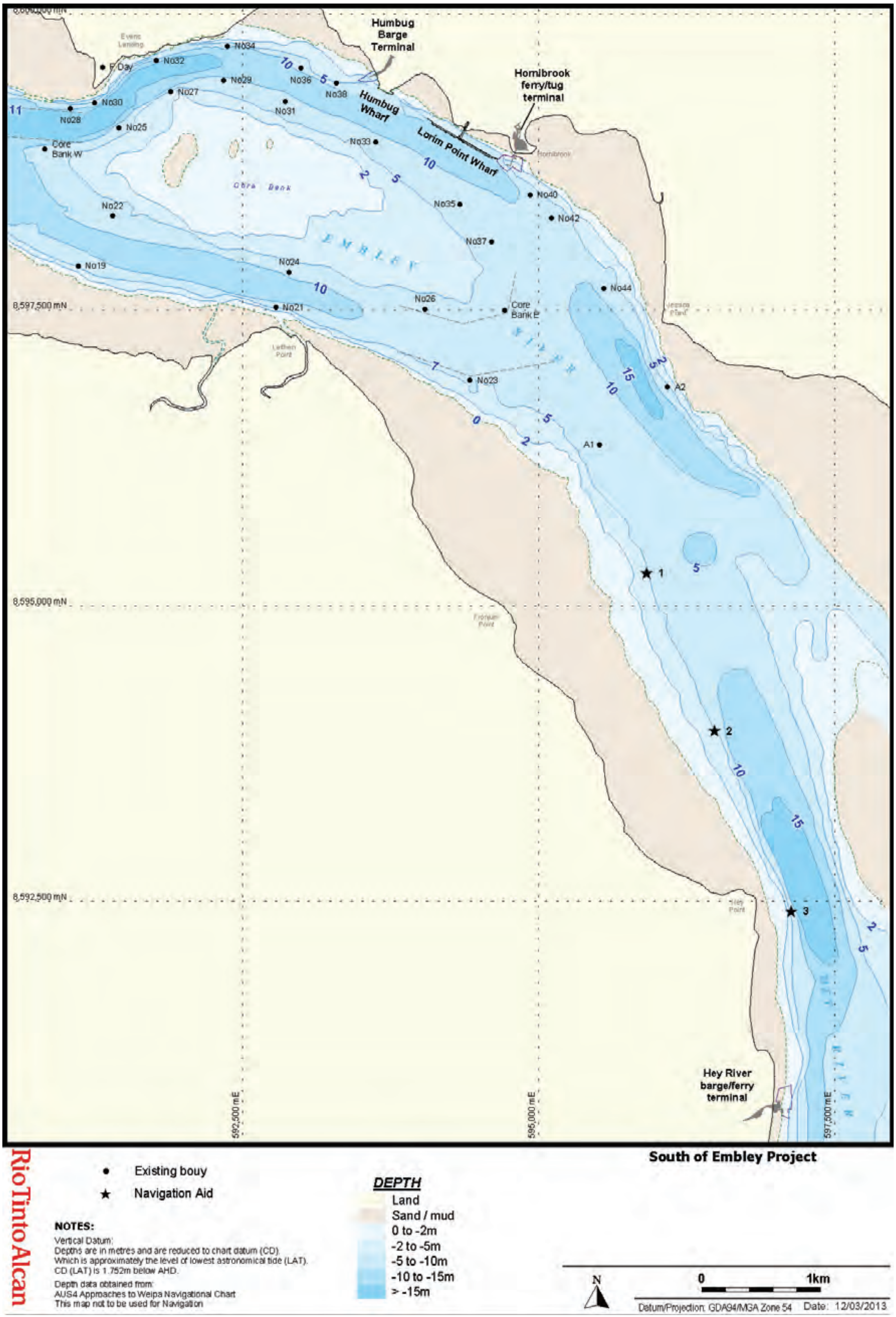
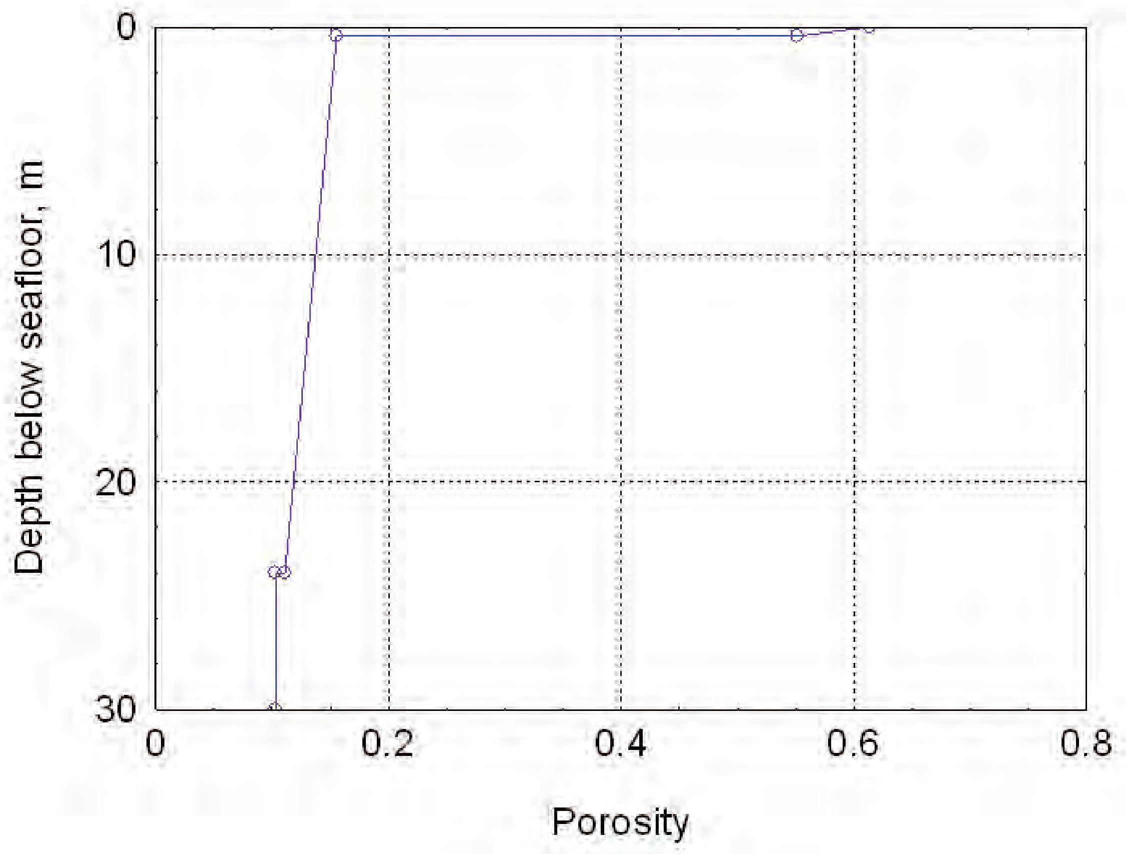
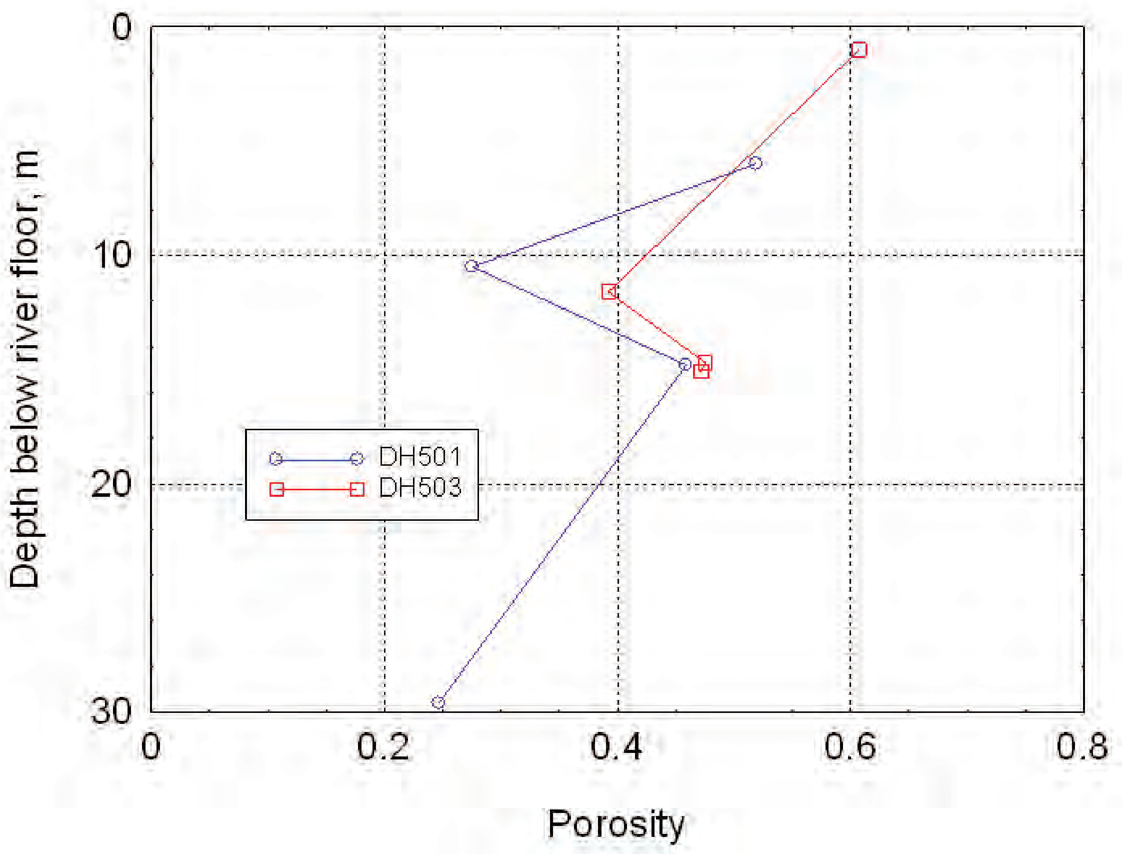


Figure 7: Contour bathymetry of the Embley River during LAT (add 3.4 m for HAT)



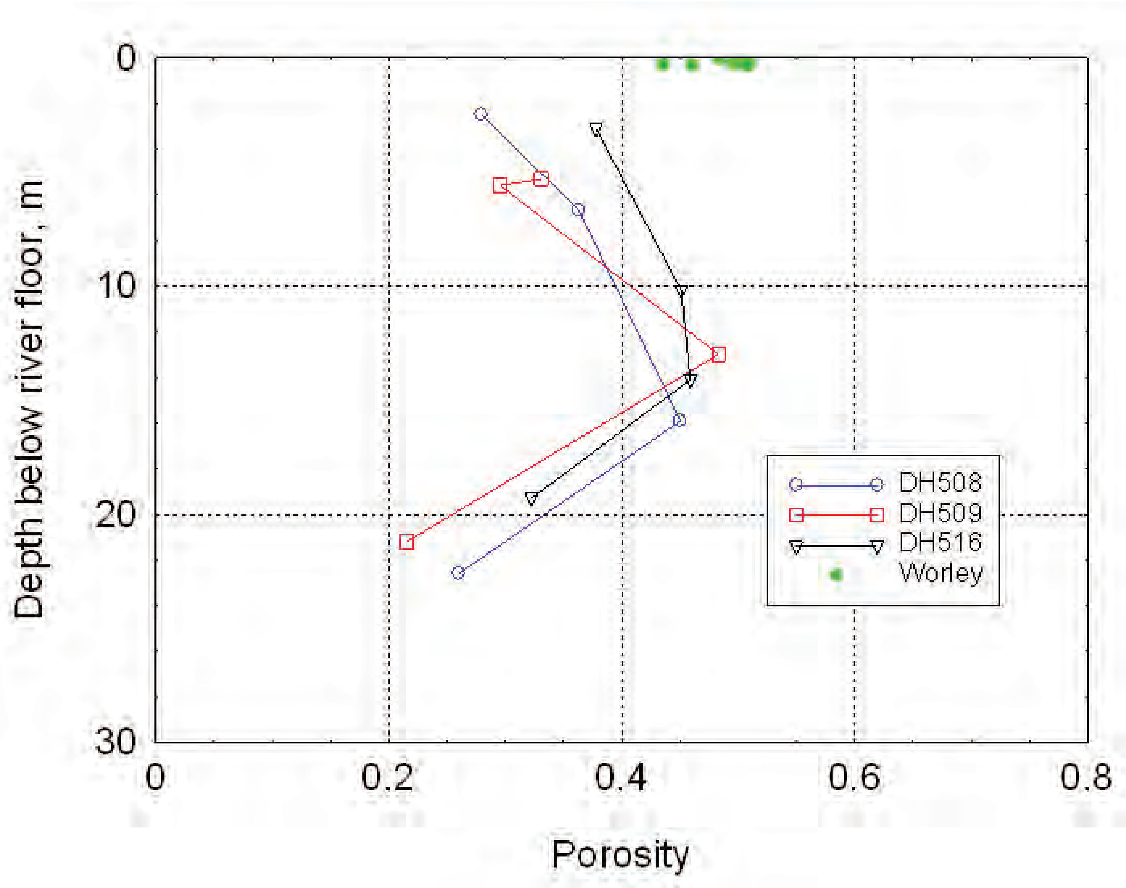
Note: derived from seismic refraction and reflection measurements of the sound speed profile approximately 500 m along the outward channel from the west end of the wharf

Figure 8: Porosity profile of the seabed at the proposed Port



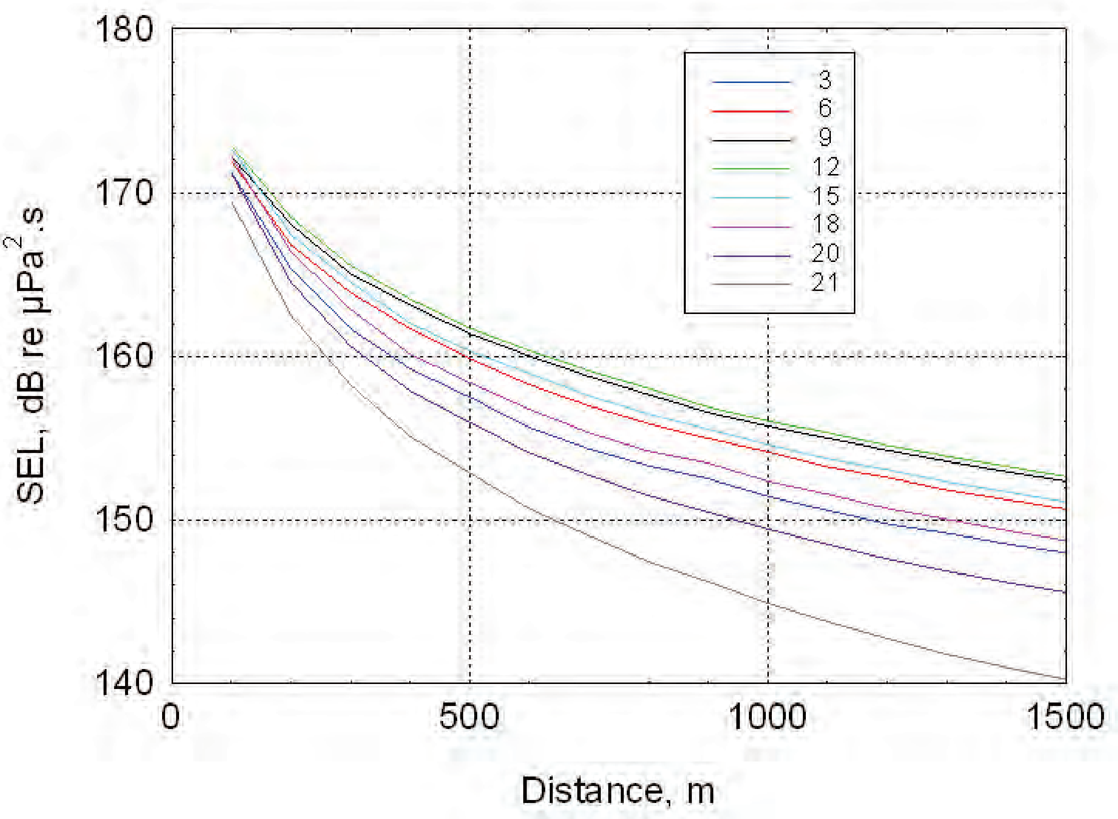
Note: derived from measurements of moisture content in Drill Holes 501 and 503

Figure 9: Porosity profiles of the riverbed at Hornibrook terminal



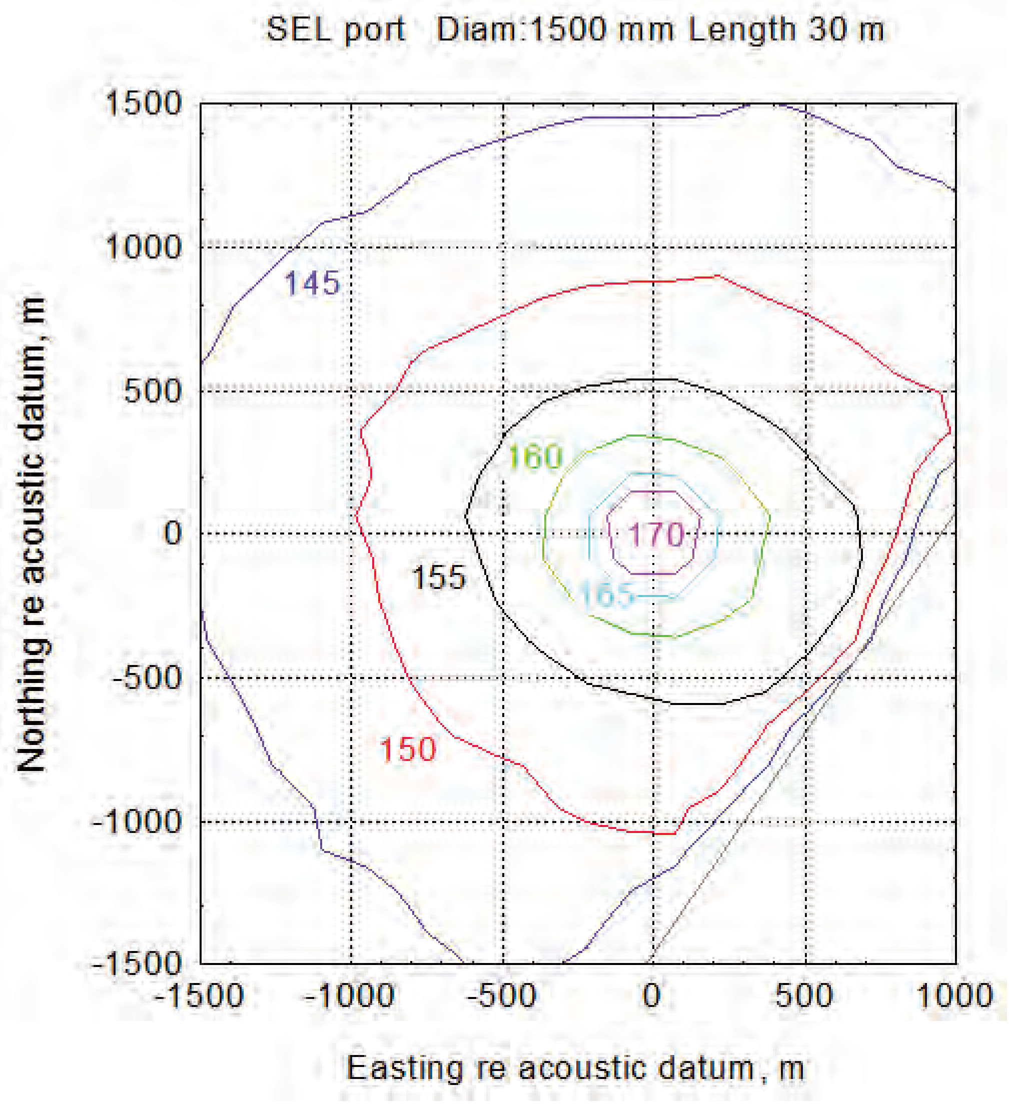
Note: derived from Coffey's measurements of Moisture Content in Drill Holes 508, 509 and 516, and Worley-Parsons' measurements of seven shallow samples.

Figure 10: Porosity profiles of the riverbed at Hey River terminal



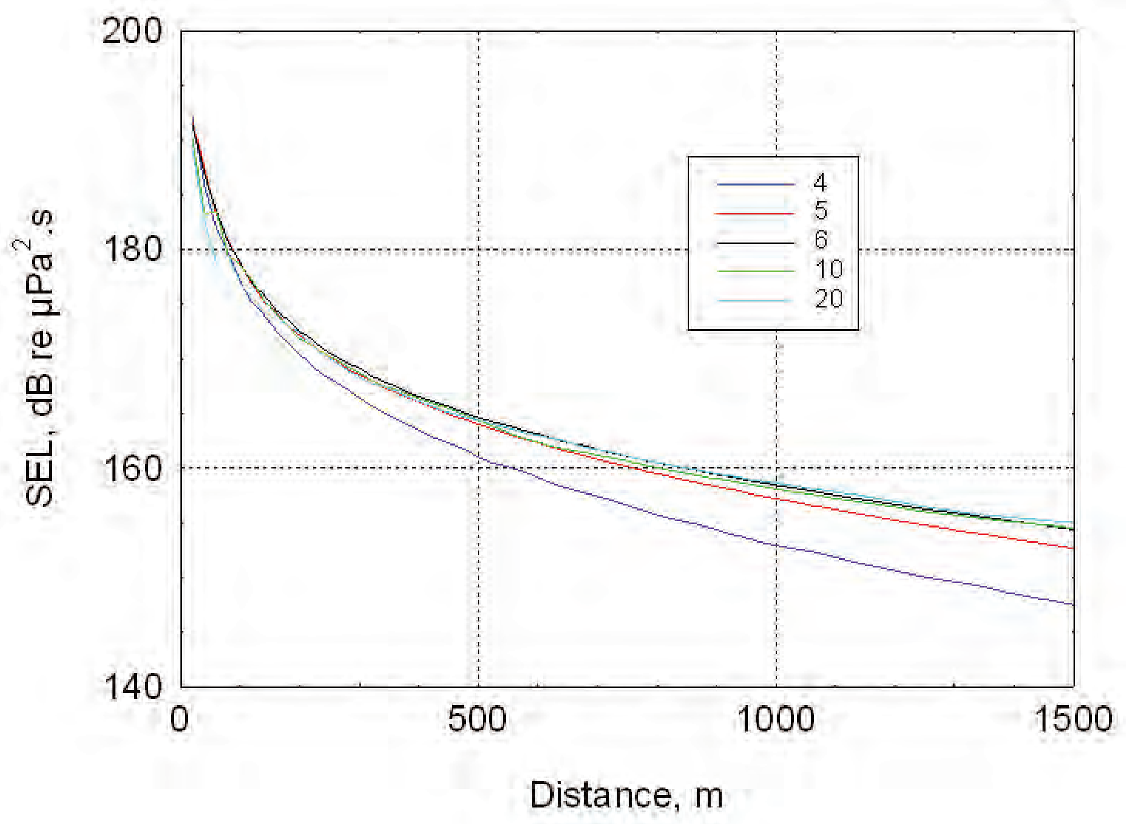
Note: for a fixed seafloor depth of 21 m, and eight values of receiver depth as indicated in the legend (source depth 10.6 m)

Figure 11: SEL as a function of distance at the proposed Port



Note: for sound source with SELSL of 211 dB re µPa2.s (95% confidence level for single blow by a 368-kJ hammer on a 1500-mm pile). (Ggrey line is approximate shoreline)

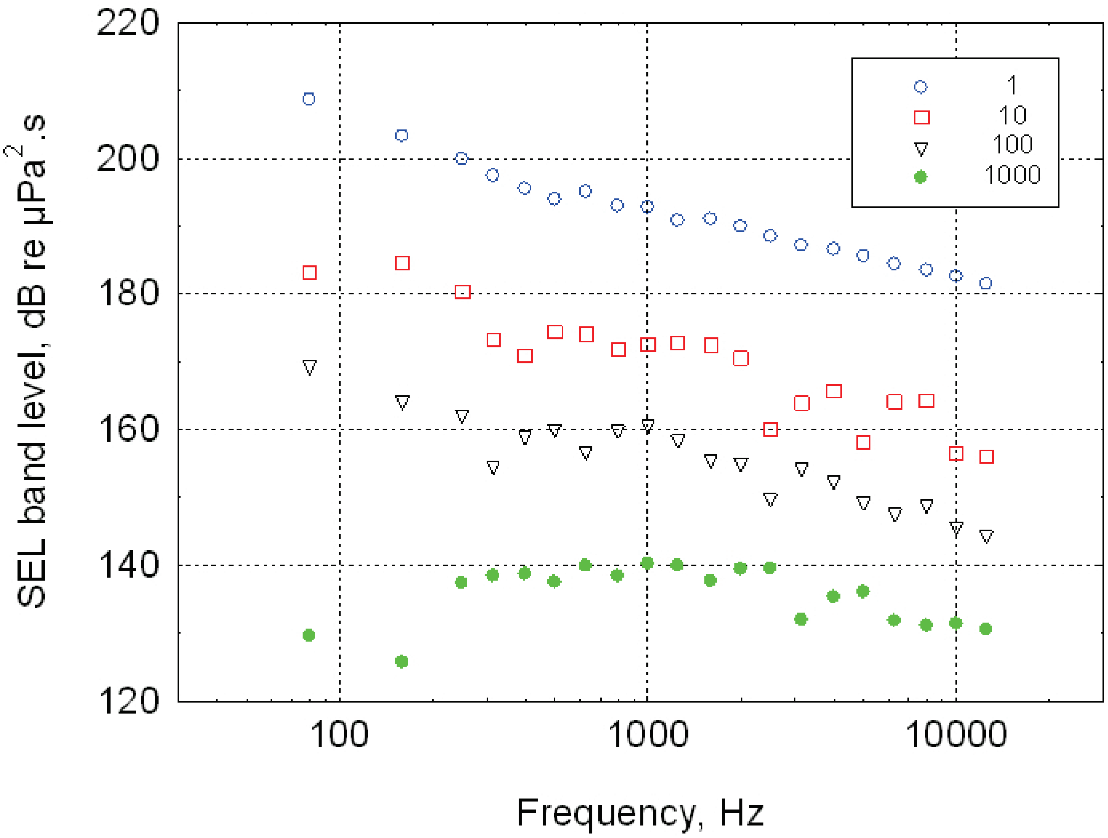
Figure 12: Predicted SEL contours around the proposed Port



Note: For sound source with SELSL of 211 dB re µPa2.s.

Applicable to five constant seafloor depths, as indicated in the legend. Source depth 3m, receiver depth 3m.

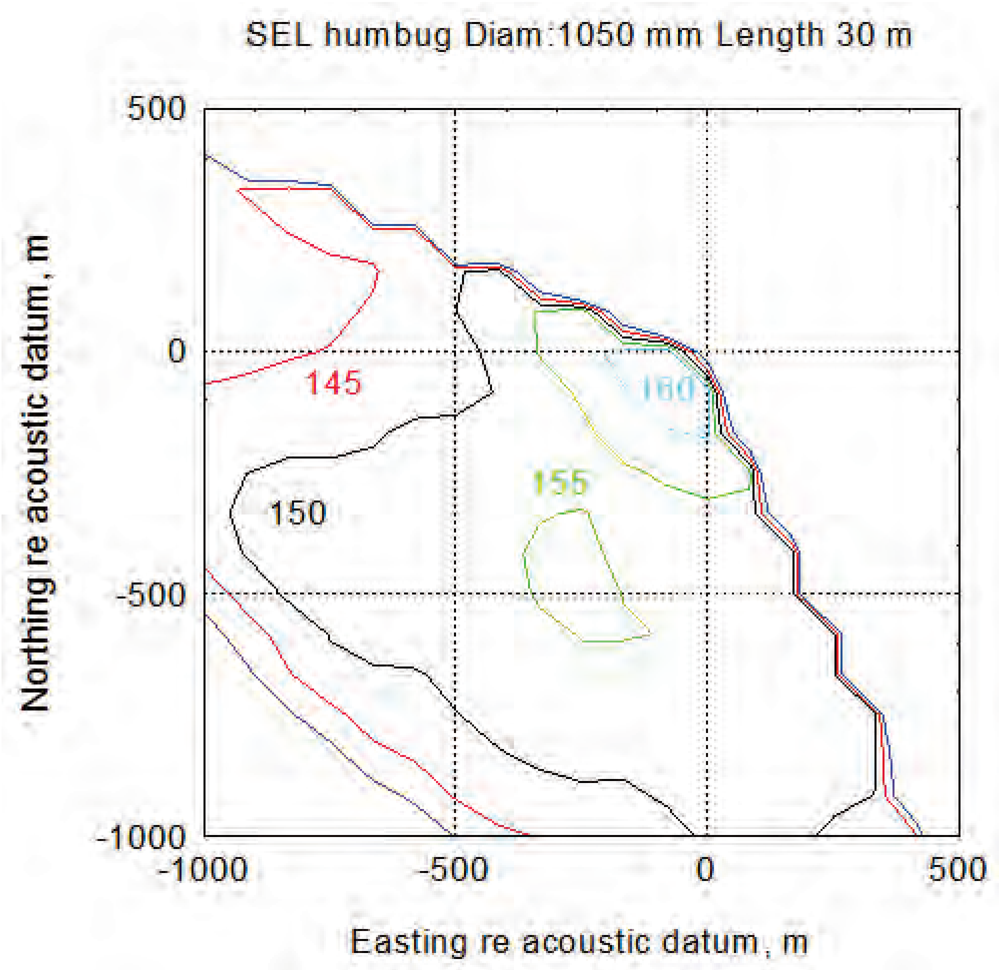
Figure 13: Predicted SEL versus distance



Note: Determined on the outbounddredge channel from the Port datum, at four distances as specified in the legend.

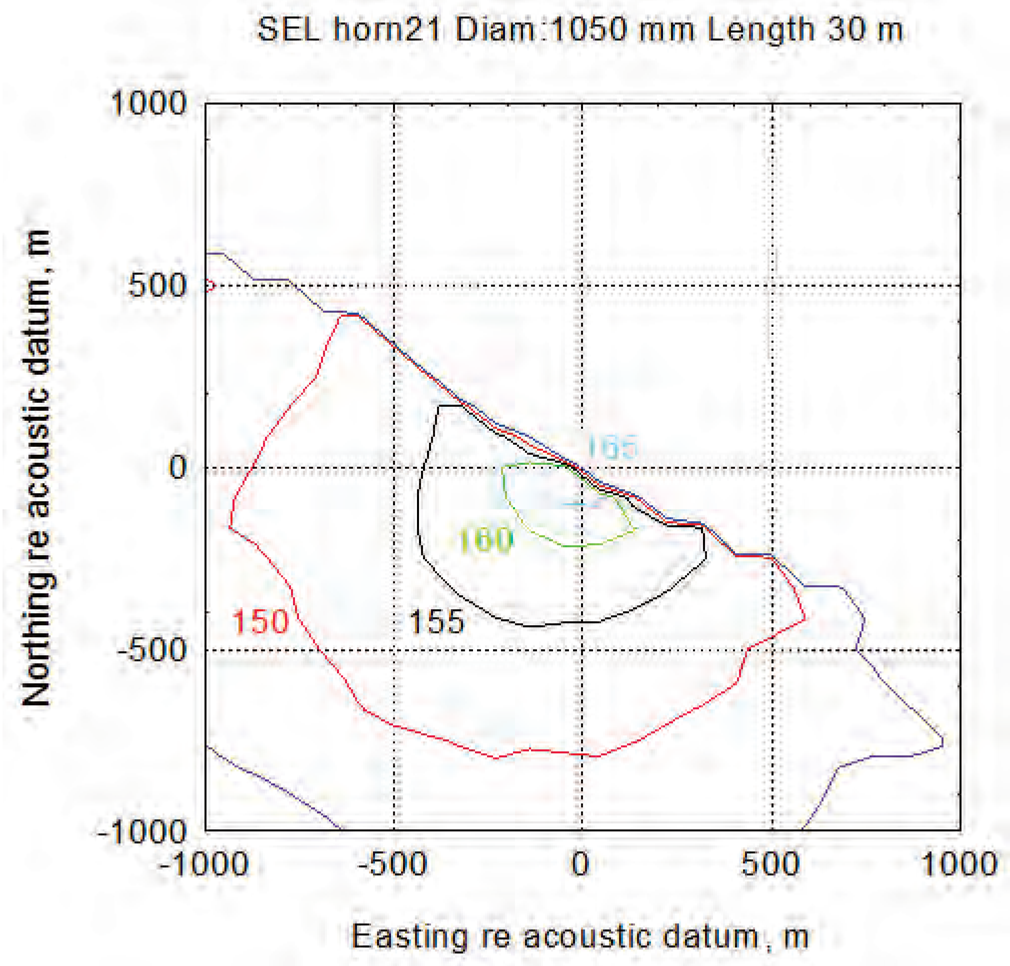
Sound source is 10.6 m deep and has a wideband SELSL of 211 dB re µPa2.s. Receiver depth is 3 m.

Figure 14: Third-octave band-level spectra of SEL per blow at the proposed Port



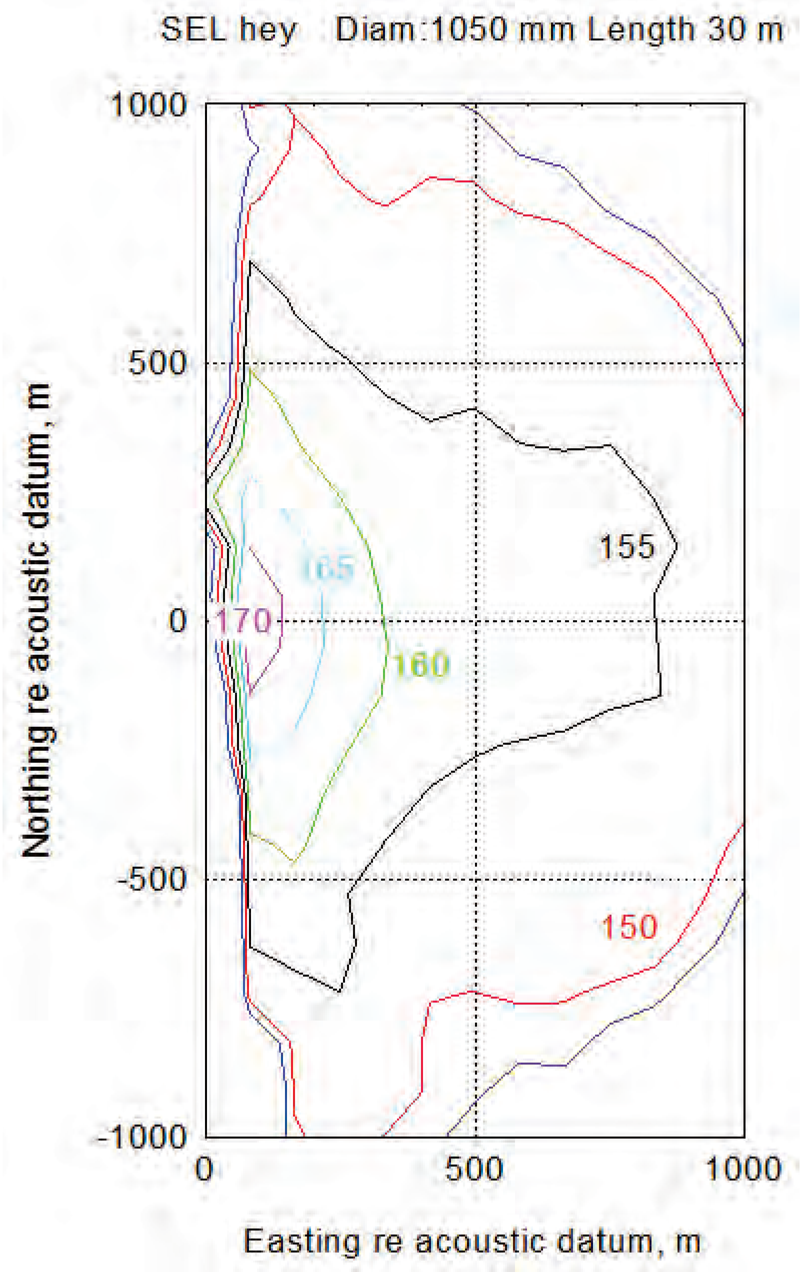
Note: Determined for sound source with SELSL of 208 dB re µPa2.s (95% confidence level for single blow by a 235-kJ hammer on a 1050-mm pile)

Figure 15: Predicted SEL contours around Humbug terminal



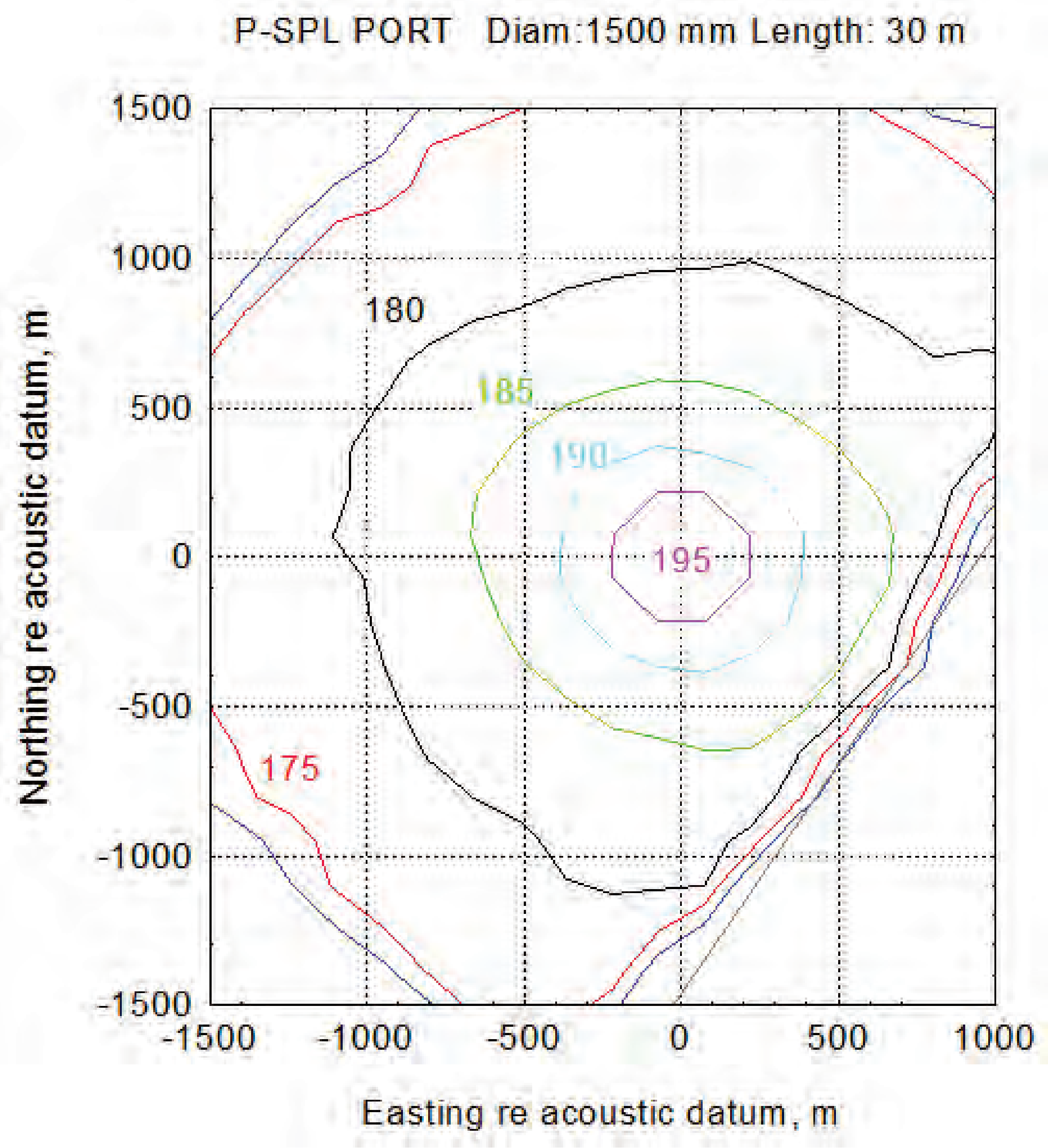
Note: Determined for sound source with SELSL of 208 dB re µPa2.s (95% confidence level for single blow by a 235-kJ hammer on a 1050-mm pile)

Figure 16: Predicted SEL contours around Hornibrook terminal



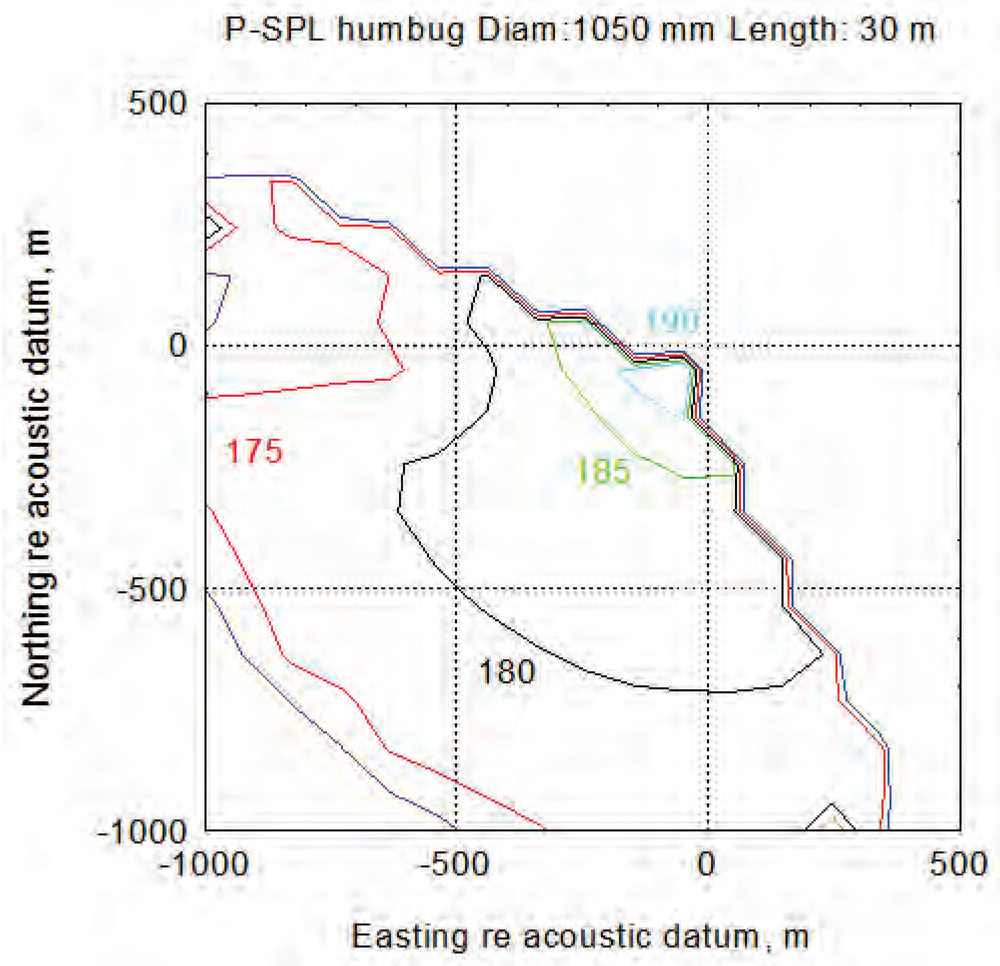
Note: Determined for sound source with SELSL of 208 dB re µPa2.s (95% confidence level for single blow by a 235-kJ hammer on a 1050-mm pile)

Figure 17: Predicted SEL contours around Hey River terminal



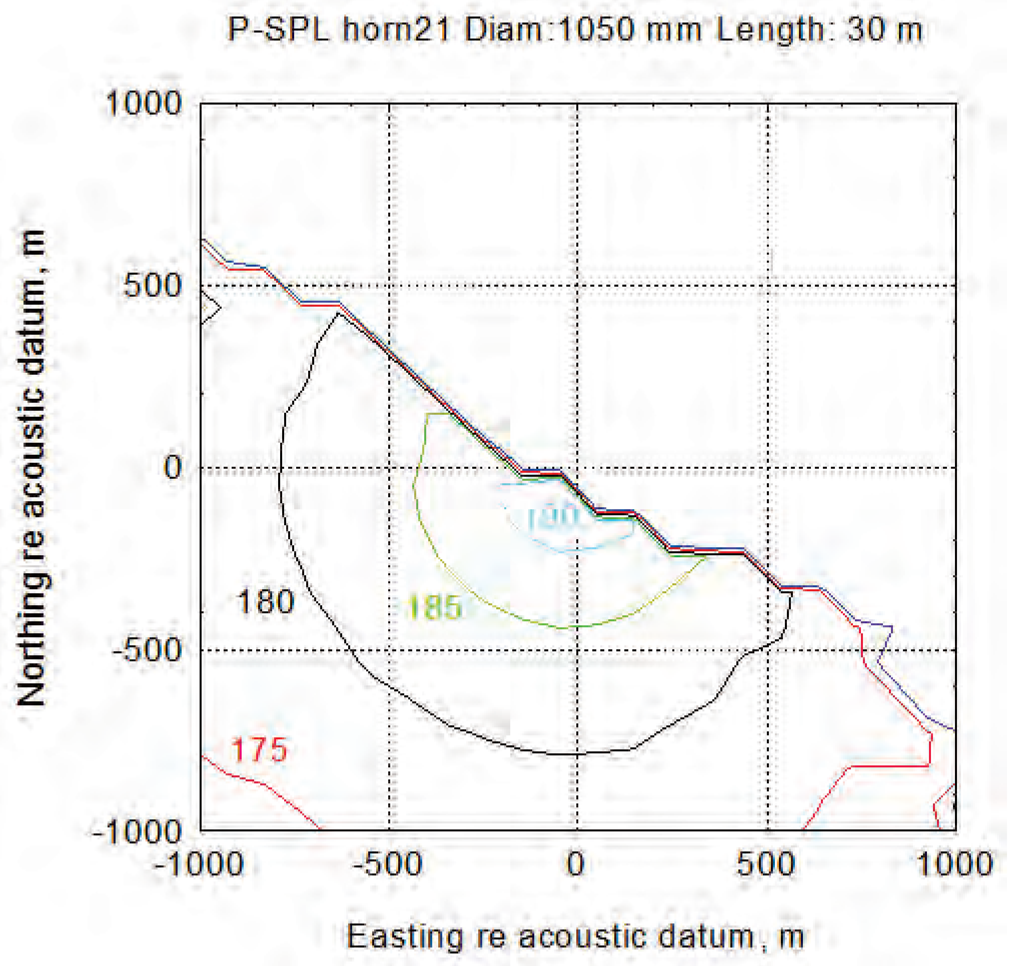
Note: Determined for sound source with P-SPLSL of 242 dB re μPa2 (95% confidence level for blows by a 368-kJ hammer on a 1500-mm pile) (grey line is approximate shoreline)

Figure 18: Predicted P-SPL contours around the proposed Port



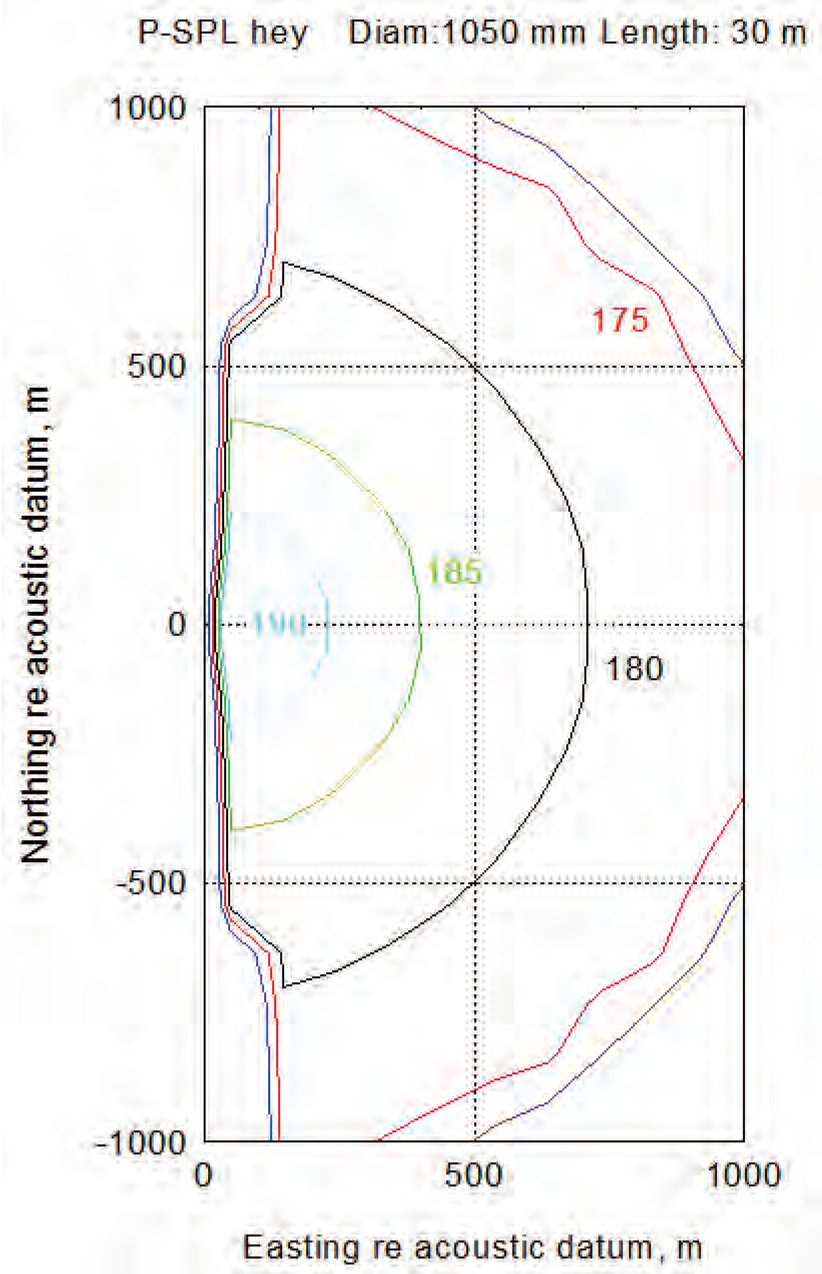
Note: Determined for sound source with P-SPLSL of 237 dB re μPa2 (95% confidence level for blows by a 235-kJ hammer on a 1050-mm pile with 5.4-m SFD)

Figure 19: Predicted P-SPL contours around Humbug terminal



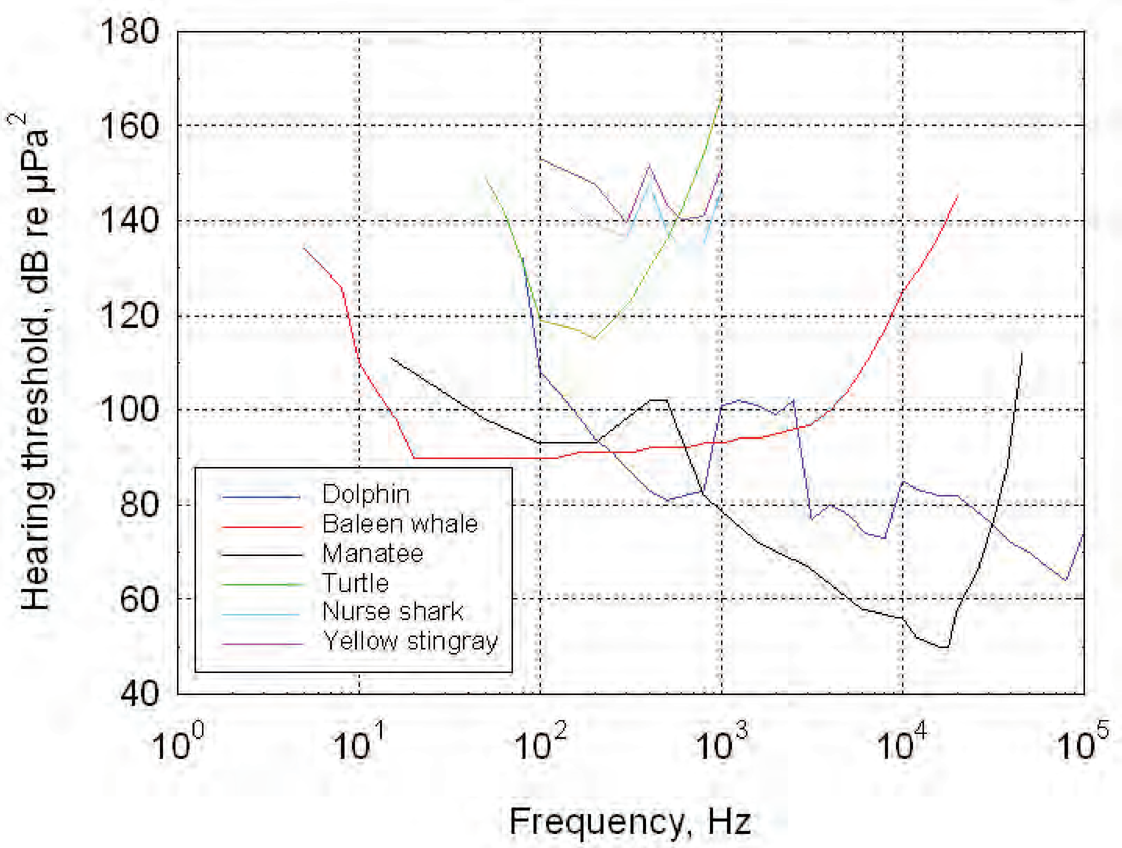
Note: Determined for sound source with P-SPLSL of 238 dB re μPa2 (95% confidence level for blows by a 235-kJ hammer on a 1050-mm pile with 10.6-m SFD)

Figure 20: Predicted P-SPL contours around Hornibrook terminal



Note: Determined for sound source with P-SPLSL of 237 dB re µPa2 (95% confidence level for blows by a 235-kJ hammer on a 1050-mm pile with 5.4-m SFD)

Figure 21: Predicted P-SPL contours around Hey River terminal



Key: Blue Line - Bottlenose Dolphin (representative of: Indo-pacific Humpback and Australian Snubfin Dolphin); Red line - Baleen whale (representative of: Bryde's Whale); Black line - Manatee (representative of: Dugong); Green line - marine turtle; Turquoise line - Nurse Shark (representative of: Speartooth Shark); and Magenta line - Yellow Stingray (representative of: sawfish).

Figure 22: Audiograms representative of the aquatic animals potentially impacted by construction noise

Appendix B - References

Bailey H, Senior B, Simmons D, Rusin J, Picken G and Thompson PM 2010, "Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals", *Marine Pollution Bulletin* volume 60, pages 888–897.

Beale, C.M. (2007) "The behavioural ecology of disturbance responses". *International Journal of Comparative Psychology*. Vol. 20: pp 111-120.

Brekhovskikh, LM 1960 *Waves in Layered Media* (English translation), New York: Academic.

Brekhovskikh, LM and Lysanov Y 1982 *Fundamentals of ocean acoustics* (English translation), Berlin: Springer-Verlag.

Carlson, TJ and Weiland, MA 2007, *Dynamic pile driving and pile driving underwater impulsive sound*, Battelle–Pacific Northwest Division, Richland, Washington,USA

Casper, BM 2006, *The hearing abilities of elasmobranch fishes* (PhD dissertation), University of South Florida, Tampa, Florida

Coffey 2008 *Marine geophysical study South of Embley (SoE) Development*, Coffey Geotechnics Pty Ltd, Lane Cove West NSW, 23pp.

Coffey 2009 *Rio Tinto Alcan, South of Embley feasibility study, Offshore Geotechnical Investigation Interpretative Report*. Coffey Geotechnics Pty Ltd, Newstead QLD, 75pp.

Collins, MD 1998 "A split-step Pade solution for the parabolic equation method," *Journal of the Acoustical Society of America*, vol. 93, pp. 1736–1742.

DeRuiter, S.L. and Doukara, K.L. (2012) "Loggerhead turtles dive in response to airgun sound exposure". *Endangered Species Research*. Vol. 16(1): pp 55-63.

Duncan, AJ, McCauley, RD, Parnum, I and Salgado-Kent, C. 2010, "Measurement and modelling of underwater noise from pile driving", *Proceedings of 20th International Congress on Acoustics ICA 2010*, Sydney. http://www.acoustics.asn.au/conference_proceedings/ICA2010/cdrom-ICA2010/papers/p26.pdf

Erbe, C 2009 "Underwater noise from pile driving in Moreton Bay, Qld", *Acoustics Australia* vol. 37 No. 3, pp 87 – 92.

Erbe, C. (2012) "Effects of underwater noise on marine mammals", pp. 17-22, in A.N. Popper and A. Hawkins (eds.). *The Effects of Noise on Aquatic Life. Advances in Experimental Medicine and Biology*. New York: Springer-Verlag.

Gerstein, ER, Gerstein, L, Forsythe, SE and Blue, JE. 1999 "The underwater audiogram of the West Indian manatee (Trichechus manatus)", *Journal of the Acoustical Society of America*, vol. 105, pp. 3575–3583.

Hall, M 1986, "The effects of variations in sound speed on coupling coefficients between acoustic normal modes in shallow water over a sloping bottom", *Journal of the Acoustical Society of America*, vol. 79, pp. 332–337.

Hall, MV 2004, "Preliminary analysis of the applicability of adiabatic modes to inverting synthetic acoustic data in shallow water over a sloping seafloor", *IEEE Journal of Oceanic Engineering* vol. 29 (1), pp 51 - 58.

Hamilton, EL 1980 "Geoacoustic modeling of the seafloor", *Journal of the Acoustical Society of America*, vol. 68, pp. 1313–1340.

Hammersteel 2006, HHK 25S Hydraulic Impact Hammer, Data Sheet. Junttan. http://www.hammersteel.com/cmss_files/attachmentlibrary/Brochures/Junttan/Hydraulic%20Impact%20Hammers/junttan-hhk-s-series-25s.pdf

Hodgson, A.J. and Marsh, H. (2007) "Response of dugongs to boat traffic. The risk of disturbance and displacement". *Journal of Experimental Marine Biology and Ecology* vol. 340: pp 50-61.

ICF Jones and Stokes and Illingworth and Rodkin, Inc, 2009 *Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish*, ICF Jones & Stokes, Sacramento, California and Illingworth and Rodkin, Inc, Petaluma, California.

Janik, V. M. and Thompson, P. M.. 1996. "Changes in surfacing patterns of bottlenose dolphins in response to boat traffic". *Marine Mammal Science* vol. 12, pp 597-602.

Kastelein, RA, Hoek, L, Jennings, N, de Jong, CAF, Terhune, JM and Dieleman, M, (2010) *Acoustic Mitigation Devices (AMDs) to deter Marine Mammals from Pile Driving areas at sea: Audibility & Behavioural response of a Harbour Porpoise & Harbour Seals*. COWRIE Ref: SEAMAMD-09, Technical Report.

Laughlin, J 2006, *Underwater Sound Levels Associated With Pile Driving at the Cape Disappointment Boat Launch Facility, Wave Barrier Project*, Washington State Department of Transportation Office of Air Quality and Noise, Seattle Washington.

Laughlin, J 2007, *Underwater sound levels associated with driving steel and concrete piles near the Mukilteo Ferry terminal*, Washington State Department of Transportation, Seattle Washington.

Leach G.J., Delaney R. and Fukuda, Y. (2009). *Management Program for the Saltwater Crocodile in the Northern Territory of Australia, 2009 - 2014.* Northern Territory Department of Natural Resources, Environment, the Arts and Sport, Darwin.

Love, AEH 1944 *A treatise on the Mathematical Theory of Elasticity* (fourth edition), Dover Publications, New York.

Marsh, HW and Schulkin, M 1962 "Shallow water transmission", *Journal of the Acoustical Society of America* vol. 34, pp 863-864.

McCauley, R. D., Jenner, M-N., Jenner, C., McCabe, K. A., and Murdoch, J. 1998. "The response of humpback whales (Megaptera novaeangliae) to offshore seismic survey noise: Preliminary results of observations about a working seismic vessel and experimental exposures" *Australian Petroleum Production and Exploration Association Journal*, vol. 38, pp 692-707.

McCauley, R. D., Fewtrell, J., Duncan, A. J., Jenner, C., Jenner, M.-N., Penrose, J. D., et al. 2000. "Marine seismic surveys: A study of environmental implications" *Australian Petroleum Production and Exploration Association Journal*, vol. 40, pp 692-708.

McDaniel, ST 1982 "Mode coupling due to interaction with the seabed", *Journal of the Acoustical Society of America*, vol. 72, pp. 916–923.

Nedwell, J, Langworthy, J and Howell, D 2003 *Assessment of sub-sea acoustic noise and vibration from offshore wind turbines and its impact on marine wildlife; initial measurements of underwater noise during construction of offshore windfarms, and comparison with background noise*, report

Nehls, G, Betke, K, Eckelmann, S, and Ros, M 2007 "Assessment and costs of potential engineering solutions for the mitigation of the impacts of underwater noise arising from the construction of offshore windfarms". BioConsult SH report, Husum, Germany. On behalf of Cowrie Ltd, UK.

Ng, S.L. and Leung, S. (2003) "Behavioural response of Indo-Pacific humpback dolphin (Sousa chinensis) to vessel traffic". *Marine Environmental Research* Vol. 56: pp 555-567.

Nowacek, S. M., R. S. Wells and A. Solow. 2001. "Short-term effects of boat traffic on bottlenose dolphins, Tursiops truncatus, in Sarasota Bay, Florida". *Marine Mammal Science* vol. 17, pp 673-688

Rausche, F, Likins, GE, Goble, GG, Hussein, M 1986, *The performance of pile driving systems: Inspection manual*, Department of Transportation, Washington DC. http://isddc.dot.gov/OLPFiles/FHWA/009990.pdf

Reinhall PG and Dahl PH 2011, "Underwater Mach wave radiation from impact pile driving: Theory and observation", *Journal of the Acoustical Society of America*, vol. 130, pp. 1209–1216.

Richardson, MD and Briggs, KB 1993 "On the use of acoustic impedance values to determine sediment properties", *Proceedings Institute of Acoustics* (UK), Volume 15 part 2, pages 15 – 24.

RTA 2011 "Rio Tinto Alcan Environmental Impact Statement South of Embley Project - Section 4 – Climate".

Robinson SP, Lepper PA and Ablitt J 2007, "The measurement of the underwater radiated noise from marine piling including characterisation of a 'soft start' period", Proceedings of 'OCEANS 2007 - Europe' conference,

DSEWPaC 2008 *EPBC Act Policy Statement 2.1 – Interaction between offshore seismic exploration and whales*. http://www.environment.gov.au/epbc/publications/pubs/seismic-whales-background.pdf

DSEWPaC 2012 "Search Results: crocodylus porosus", Species Profile and Threats Database. http://www.environment.gov.au/cgi-bin/sprat/public/spratlookupspecies.pl?name=crocodylus+porosus&searchtype=Sciname

Southall BL, Bowles AE, Ellison WT, Finneran JJ, Gentry RL, Greene Jr CR, Katsak D, Ketten DR, Miller JH, Nachtigall PE, Richardson WJ, Thomas JA, Tyack PL 2007. "Marine Mammal Noise-Exposure Criteria: Initial Scientific Recommendations", *Aquatic Mammals*, volume 33, issue 4, pp 411 - 521.

Tech Environmental, Inc 2006. *Final EIR Underwater Noise Analysis* , Tech Environmental, Inc (Report 5.3.2-2), Waltham, Massachusetts**Error! Hyperlink reference not valid.**

Vagle, S 2003 *On the impacts of pile-driving noise on marine life* (internal report), Ocean Science and Productivity Division, Institute of Ocean Sciences, Sidney, British Columbia.

Ward, P 2012 *Underwater noise impact study in support of the Oyster Wave Energy Project, Isle of Lewis*, Technical Report, Kongsberg Maritime, Aberdeen, Scotland (prepared for Aquamarine Power, Edinburgh, Scotland).

Weston, DE 1960 “A Moire fringe analog of sound propagation in shallow water”, *Journal of the Acoustical Society of America*, vol. 32, pp. 647–654.

Westwood, EK, Tindle, CT and Chapman, NR 1996 “A normal mode model for acousto-elastic ocean environments,” *Journal of the Acoustical Society of America*, vol. 100, pp. 3631–3645.

Worley Parsons 2010. *South of the Embley Project: 185,000 DWT vessel port development plan Sediment Characterisation Report*, Worley Parsons Infrastructure & Environment, Brisbane.

Worley Parsons 2011. *South of the Embley Project Barge/Ferry Terminals Sediment Characterisation Study*, Worley Parsons Infrastructure & Environment, Brisbane.

Zhang ZY and Tindle CT 1995 “Improved equivalent fluid approximations for a low shear speed ocean bottom”, *Journal of the Acoustical Society of America*, vol. 98, pp. 3391–3396.