UNDERWATER NOISE FROM PILE DRIVING IN MORETON BAY, QLD

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This article presents measurements of underwater pile driving noise recorded during the construction of the duplicate Houghton Highway bridge in western Moreton Bay, Queensland. Moreton Bay is a protected marine park, a World Heritage Site and a Ramsar Wetland, providing habitat for turtles, dugong, sharks, dolphins and whales, some species of which are listed as vulnerable to endangered. Pile driving noise was measured for small and large piles at various locations and ranges. Using an acoustic propagation model, a sound map was computed for Bramble Bay. Sound levels were compared to currently available information on impact thresholds. Ranges greater than those corresponding to impact thresholds were scanned for the absence of dolphins before and during pile driving in line with a monitoring and response plan.

INTRODUCTION

In 2008, construction of the duplicate Houghton Highway Bridge began north of Brisbane in western Moreton Bay, Queensland, Australia. Moreton Bay is a marine park, listed as a World Heritage and Ramsar Wetland. Of the marine animals living in Moreton Bay, the Environment Protection and Biodiversity Conservation (EPBC) Act 1999 lists the humpback whale (*Megaptera novaeangliae*), the green turtle (*Chelonia mydas*) and the hawksbill turtle (*Eretmochelys imbricata*) as vulnerable, the loggerhead turtle (*Caretta caretta*) as endangered, and the grey nurse shark (*Carcharias taurus*) as critically endangered. Dugong (*Dugong dugon*) are listed as vulnerable and Indo-Pacific humpback dolphins (*Sousa chinensis*) as rare under the Nature Conservation Act 1992 of Queensland.

With sound travelling much better under water than light, marine animals, in particular marine mammals, rely on acoustics for sensing their environment. Man-made underwater noise has the potential to mask marine mammal communication sounds, environmental sounds (e.g. surf) useful for navigation, predator sounds, prey sounds, and odontocete (toothed whale) echolocation sounds. Noise can alter animal behaviour, animal distribution and habitat usage patterns. At very high levels and under certain circumstances, underwater noise can cause physiological damage to tissues and organs [1].

Pile driving source levels are among the highest of construction activities [2]. In soft substrates vibratory pile drivers are used. They contain a system of counter-rotating eccentric weights, arranged such that horizontal vibrations cancel out while vertical vibrations get transmitted into the pile from above. The sound from vibratory pile driving is continuous and has lower sound levels compared to impact pile driving. A diesel impact pile driver drops a weight through a cylindrical tube onto the pile compressing and heating the air above the pile to the ignition point of diesel fuel injected into the cylinder. The detonation drives the weight back up. Alternatively, the weight can be lifted by means of hydraulics or steam.

When the hammer strikes the pile, sound is created in air at the top of the pile. Acoustic energy spreads as a spherical pressure wave through the air. The impact also gives rise to a stress wave travelling down the length of the pile. This wave couples with the surrounding medium (first air, further down water), radiating acoustic energy into the air and water. The stress wave in the pile also couples with the substrate below the water, creating an acoustic wave travelling through the seafloor. Sound travels as compressional pressure (P) waves and transversal shear (S) waves through the elastic seafloor. Sound can travel very fast and with low attenuation through certain types of seafloor. At some distance away from the pile, acoustic energy can radiate back into the water column from the seafloor. The sound from impact pile driving is transient and discontinuous, called pulsed. Within the water column, the arrival of acoustic pulses from different media and directions and with different phases and time delays tends to result in a complex pattern of higher and lower noise level regions, in particular close to the source.

The level of noise received in the water column at some distance from the pile depends on a multitude of factors, including the size, shape, length and material of the pile, the size and energy of the hammer, the type of sediment and the thickness of the sediment, the type and depth of the underlying bedrock, the water depth, bathymetry, salinity and temperature.

MATERIALS AND METHODS

Two types of hollow steel piles were driven during bridge construction: 624 temporary piles (75cm outer diameter, 12.7mm wall thickness, 28m length) and 156 permanent piles (150cm outer diameter, 25mm wall thickness, 30m length). Underwater noise was recorded from two temporary piles at Pier 2 (on the Brighton shore; 14.5.2008), one permanent pile at Pier 2 (26.7.2008), one permanent pile at Pier 26 and four temporary piles at Pier 29 (19 & 20.3.2009). Temporary and permanent piles were driven with hydraulic piston hammers (Figure 1), model BSP-CG180 (12t weight, 180kJ maximum energy) and model IHC-S280 (14t weight, 280kJ maximum energy) respectively. Temporary piles were driven to about 23m below the seafloor, permanent piles to 26m.

Figure 1: Photo of a temporary pile being driven at Pier 2. The existing Houghton Highway bridge can be seen in the background.

Four different systems were utilized to simultaneously record underwater sound at four different locations and ranges from the piles. The first two systems were autonomous and deployed for 2h at ranges > 200m (Sites 1 & 2). The last two systems were operated manually from a barge drifting close to the piles being driven.

- Geospectrum Technology Inc. hydrophone model M15C (sensitivity -202 dB re 1V/µPa) connected to a Multi Electronique data logger model AURAL-M2. Bandwidth 16384 Hz.
- High-Tech Inc. hydrophone model HTI 96 (sensitivity -164 dB re 1V/µPa) connected to a Multi Electronique data logger model AURAL-M2. Bandwidth 16384 Hz.
- Reson hydrophone model TC4034 (sensitivity -218 dB re 1V/µPa) with external amplifier from Reson model EC6067 connected to a SoundDevices data logger model SDD 722. Bandwidth 48000 Hz.
- Reson hydrophone model TC4043 (sensitivity -201dB re 1V/µPa) connected to a SoundDevices data logger model SDD 722. Bandwidth 48000 Hz.

Frequency responses of the hydrophones and recording systems are measured in the lab every 2 years. In the field, before deployment and after recovery, each recording system was calibrated using a G.R.A.S. pistonphone calibrator model 42AC. The system gain was computed from the recorded calibration signal and applied to the digital recording data to yield sound pressure in units of µPa.

Pile driving and recording locations were measured with a GPS. Distances close to the piles were measured with a Bushnell laser range finder. Water temperature and conductivity were measured with a CTD from AquiStar, model CT2X. The water depth was 1m at Piers 2 & 26 at the time of recording and 1.5m at Pier 29.

Sound metrics

Peak sound pressure level [dB re 1µPa]:

$$SPL_{Pk} = 20\log_{10} (\max(|p(t)|)$$

where $p(t)$ is the time series of pressure measured in the water column.

Peak-to-peak sound pressure level [dB re 1µPa]:

$$SPL_{Pk\text{-}Pk} = 20\log_{10} (\max(p(t)) - \min(p(t)))$$

Root-mean-square (rms) sound pressure level [dB re 1µPa]:

$$SPL_{rms} = 20\log_{10}\left(\sqrt{\frac{1}{T_{90}}\int_{T_{90}} p(t)^2\,dt}\right)$$

where the integral runs over the duration of the pulse, defined as the time over which 90% of the total energy is received. On a cumulative energy curve, the start-time of a pulse is taken at the 5% cumulative energy mark, and the end-time of a pulse is taken at the 95% cumulative energy mark.

Sound exposure level [dB re 1 µPa^2·s]:

$$SEL = 10\log_{10} (\int_T p(t)^2\, dt)$$

which is proportional to the total energy of a plane wave.

1/3 octave band levels: SPL and *SEL* can be computed in a series of adjacent bands, each 1/3 of an octave wide. The following centre frequencies (*fc*) were used: 10, 13, 16, 20, 25, 32, 40, 50, 63, 80, 100, 126, 160, 200, 251, 320, 400, 500, 640, 800, 1000, 1280, 1585, 2000, 2560, 3162, 4000, 5120, 6310, 8000, 10000, 12589, 15849, 20000, 31623, 40000 Hz. Bandwidth (Δf) increases with increasing fc: $\Delta f = (2^{1/6} - 2^{-1/6}) \times fc$.

Power spectrum density levels [dB re 1µPa^2/Hz] give the mean squared sound pressure in a series of adjacent bands of a constant 1 Hz width.

Percentiles: The xth percentile is the level below which the signal falls x% of the time. The 50th percentile is equal to the median.

Sound propagation model

Sound propagation was modelled by the Range-dependent Acoustic Model (RAM) [3]. It is based on the parabolic equation method, assuming that outgoing energy dominates over scattered energy and computing the solution for the outgoing wave equation. As an extension to RAM, shear wave conversion at the sea floor was approximated by the equivalent fluid complex density approach [4]. RAM yields transmission loss data in 2D as a function of range and depth. To achieve a 3D sound level map, RAM was run for a fan of radials from the source, and a tessellation algorithm utilized to seed new radials as the distance between radial end points exceeded a preset resolution parameter.

Table 1: Sound propagation parameters. Depths are below the seafloor.

Depth [m]	Density [g/cm³]	P-wave speed [m/s]	P-attenuation [dB/λ]
0	1.80	1650	0.165
10	1.60	1700	0.170
20	1.62	1750	0.175
30	1.65	1800	0.180
35	2.40	2900	0.348
40	2.40	3000	0.360
50	2.50	3500	0.420
200	2.58	3800	0.456
2000	2.60	4000	10

The sound propagation model required the geoacoustic input parameters listed in Table 1. A seismic reflection survey and a series of bore hole drillings to 30-35m depth were done by Mapping and Hydrographic Surveys Pty Ltd and the Geotechnical Branch of the Dept. of Main Roads, providing P-wave sound speed profiles. Data for attenuation, density and shear waves were taken from standard reference works [5]. Shear speed was modeled at 418 m/s, shear attenuation at 0.5 dB/ λ. Data below 40m were extrapolated from tables [5]. The sound propagation model assumed an absorbing layer at 2000m depth. The speed of sound in the water column was computed from our temperature and conductivity measurements [6] and was about 1530 m/s in this shallow water.

RESULTS

Pressure waveform

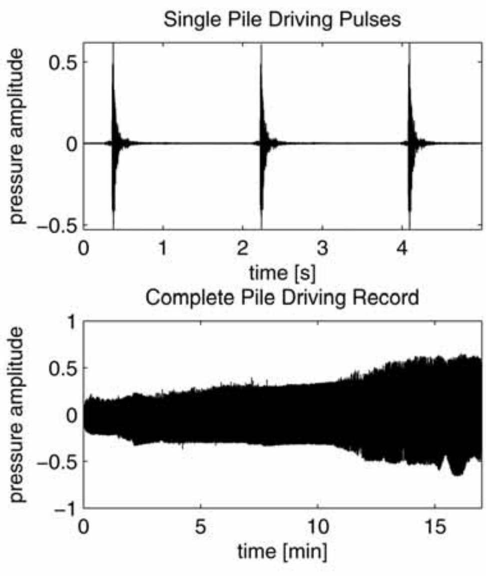

Figure 2: Pile driving waveforms. Single pulses cannot be resolved in the 17min recording.

The acoustic pressure time series recorded underwater exhibited a series of pulses, each pulse corresponding to a single strike of the pile. The pressure rose sharply and then in a dampened oscillation reduced to ambient levels. Figure 2 shows three single pulses recorded at Site 2 from a temporary pile at Pier 29. The interpulse (hammering) interval was 1.8s. Also shown is the complete (17 min) acoustic trace recorded from this pile. The pressure amplitude (not calibrated in this plot) rose by a factor 4 (=12 dB) from the beginning of the trace to the end, because of increasing pile driving energy and increasing resistance. We observed the same increase at Pier 2.

Sound levels

Figure 3 shows the received *SEL* of a temporary pile (driven at Pier 29) and a permanent pile (from Pier 26) recorded at various ranges. *SEL* decreased with range due to propagation losses. The larger permanent piles had higher received levels than temporary piles at similar range. Pile driving noise was very broadband (40 Hz to > 40 kHz) near the source. Absorption as a function of distance increases with frequency, so that at long ranges only energy at frequencies < 400 Hz remained. All levels were computed over two minutes of recording. The statistical variation of *SEL* was largest at low frequencies and long ranges where ambient noise was dominant.

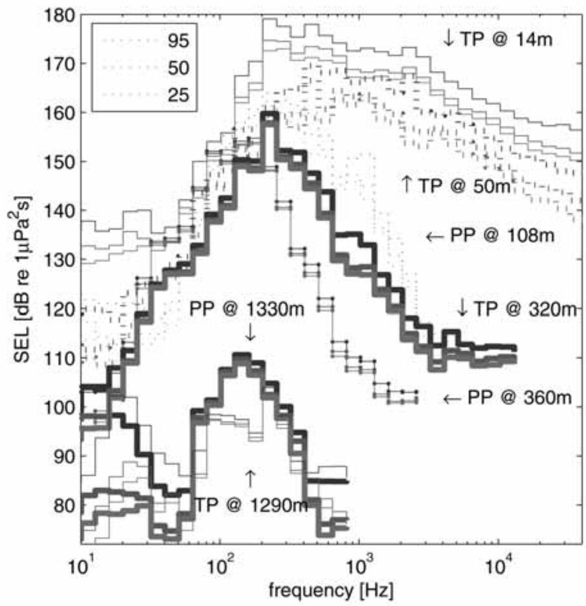

Figure 3: Measured *SEL* (in 1/3 octaves) of a temporary (TP) and a permanent pile (PP) being driven at Pier 29 and 26 respectively. Three lines are shown for each recording: the 90th, 50th and 25th percentiles from top to bottom.

Table 2 summarizes the acoustic properties of the pile driving signals that originated at Piers 26 and 29, and that were measured at different ranges. Peak-peak levels were, of course, highest, followed by peak levels. Root-mean-square levels were lower, because they represent an average pressure over the duration of a pulse. Sound exposure levels were lower still. Broadband *SEL* were computed by summing up the previously plotted 1/3 octave *SEL* on a linear (not dB) scale. The last column gives the length of the pulse. This is the duration over which the pulse energy rose from 5 to 95%. Determining the duration of a pulse is difficult, in particular if the signal is weak (at long ranges) and the background noise loud, or if the pulse is spread out due to dispersion and due to time-lagged arrivals of energy via different propagation paths.

Table 2: Summary of noise level measurements. Means ± standard deviations are given. *: The permanent pile value @ 14m came from Pier 2.

Range [m]	SPL_{PkPk} [dB re 1μPa]	SPL_{Pk} [dB re 1μPa]	SPL_{rms} [dB re 1μPa]	SEL [dB re 1μPa^{2}s]	Pulse Length [ms]
Temporary Pile @ Pier 29 water depth 1.5m					
14	213 ± 2	207 ± 2	194 ± 2	183 ± 2	69 ± 13
51	205 ± 2	199 ± 2	185 ± 2	173 ± 2	59 ± 16
(Site 2) 320	187 ± 1	181 ± 1	173 ± 1	160 ± 1	50 ± 4
(Site 1) 1290	132 ± 1	126 ± 1	115 ± 1	107 ± 1	142 ± 74
Permanent Pile @ Pier 26 water depth 1m					
14*	211 ± 2	205 ± 2	189 ± 1	179 ± 1	94 ± 28
108	198 ± 2	192 ± 2	183 ± 1	168 ± 1	28 ± 3
(Site 2) 360	186 ± 1	180 ± 1	172 ± 1	158 ± 1	36 ± 3
(Site 1) 1330	138 ± 1	133 ± 1	124 ± 1	114 ± 1	101 ± 64

For the temporary pile, the data summarized were all taken from the end of the pile driving, yielding the highest level (worst-case). For the permanent pile, levels at 360m and 1330m range were computed from the end also. At 108m, only the middle section of pile driving was recorded. No close-range data were obtained at Pier 26; the 14m value listed was measured at Pier 2 at the beginning of the pile being driven.

Ambient noise

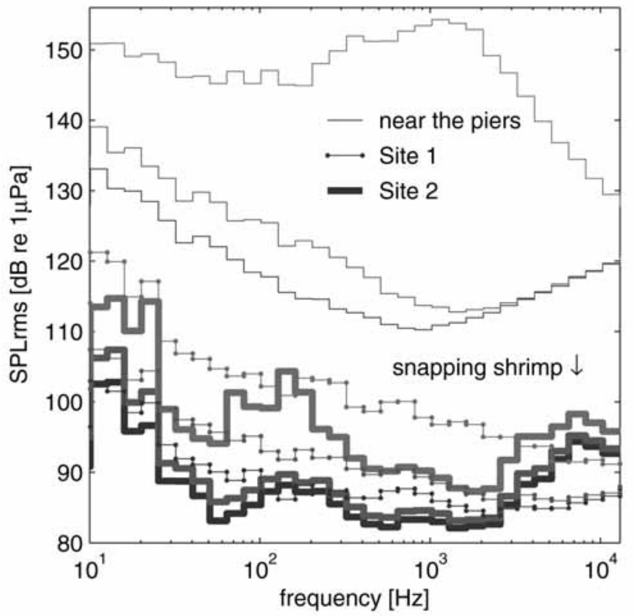

Figure 4: 1/3 octave levels of SPL_{rms} of ambient noise, computed in 1s windows, showing statistics over 15 minutes of recording. Three lines are given for each site corresponding to the 95th, 50th and 25th percentiles.

SPL_{rms} of ambient noise was computed in 1s windows and statistics were calculated for a 15 minute recording at each site. Percentiles of SPL_{rms} in 1/3 octave bands are shown in Figure 4. Close to the piers, right at the construction site, ambient noise was highest and most variable. Construction activities generated noise at low-to-mid frequencies. There were occasional peaks sounding like metal banging (e.g. banging of piles or dropping of chains and metal) to the ear. Furthermore, this site was about 10-15m from the existing Houghton Highway bridge which runs parallel to the duplicate bridge under construction. Cars driving over the existing bridge generated low-frequency noise in the water. There also was splashing and flow noise around the hydrophones, the barge and the piles. The reason why the 25th and 50th percentiles of the noise near the piers increased above 2kHz, was that the rather insensitive recording system used here ran into its noise floor, which shows up as an upslope on 1/3 octave plots (because bands get wider with increasing frequency, adding increasingly more self-noise).

The systems deployed at Sites 1 and 2 were much more sensitive. There was a bit of water flow noise in the recordings. At Site 2, the sound of snapping shrimp was clearly audible in the data. These animals are common in tropical and subtropical regions throughout the world's oceans. The snapping sound occurs when the animal snaps its claw. Near a colony of shrimp, the ambient noise sounds like continuous crackling ('frying' or 'wood burning') with energy between 2 and 24 kHz [7]. Spectra measured here matched published spectra very well [8,9]. There was quite a bit of sand swishing noise at Site 1 (sand swishing over the base of the instrument as evidenced by the presence of sand in nuts and bolts upon retrieval). Weather conditions on March 19 and 20 were cloudy with moderate wind adding to low-frequency noise. We did not see or hear any boats in the vicinity at the times of recording.

Sound propagation

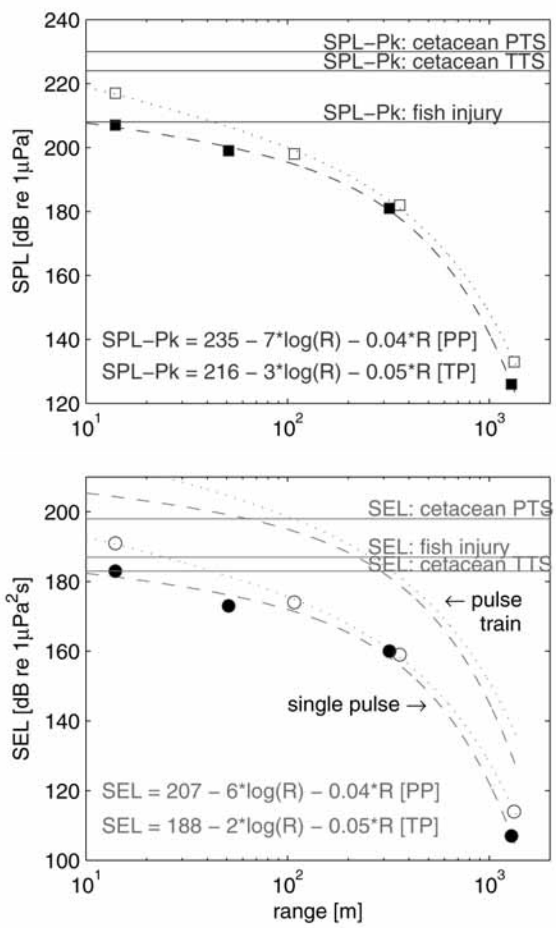

Figure 5: Received SPL_{Pk} (top) and SEL (bottom) from a permanent pile at Pier 26 (hollow symbols) and a temporary pile at Pier 29 (solid symbols). Regression for permanent pile (..), temporary pile (--). SEL as a function of range are shown for a

single pulse and a 17-minute pulse train. Current suggestions for fish and dolphin impact thresholds (solid lines). *SEL* thresholds for fish injury and cetacean TTS correspond to single pulses only.

SPL_{Pk} and *SEL* values from Table 2 were plotted in Figure 5. The permanent pile levels at 14m range were measured at the beginning of driving this pile; 12 dB (the increase from beginning to end measured at Piers 2 & 29) was added to estimate the levels at the end of driving this pile. The permanent pile levels at 108m range were recorded when the middle section was driven, and therefore enlarged by 6 dB to estimate the end levels. Regression analysis was performed using a spreading term proportional to the logarithm of range (R) and an absorption term proportional to range.

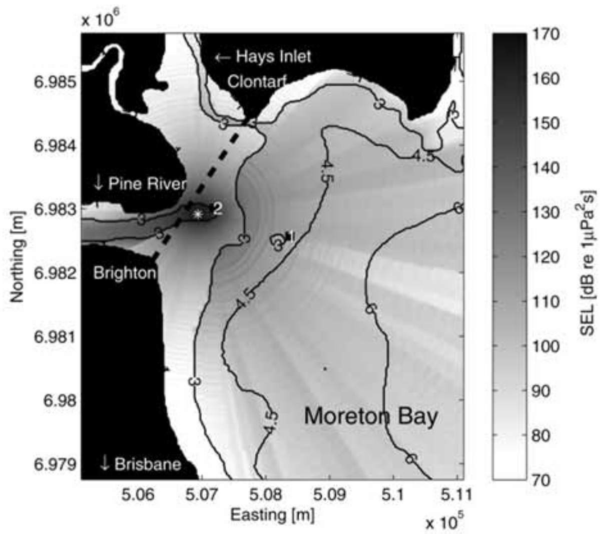

Figure 6: Modelled *SEL* from a temporary pile being driven at Pier 29 (white asterisk). Recording sites 1 & 2 marked in white. Dashed line: bridge under construction. Coordinates refer to UTM Zone 56.

Results of the 3D sound propagation model RAM are shown in Figure 6 for a temporary pile at Pier 29. Plotted are the maximum *SEL* over all depths. Sound energy got channelled into the deeper waters of Pine River and Hays Inlet. Shadowing occurred behind the circular rise near Site 1. At Site 1, the modelled level was 110 dB; compared to 107 dB measured. At Site 2, the modelled level was 151 dB compared to 160 dB measured.

DISCUSSION

Comparison with other pile driving measurements

A number of studies have recorded impact pile driving, only few data are reported in the peer-reviewed literature. Comparison is difficult, because important information is often missing (such as geoacoustics of the location, water depth, pile and hammer parameters). Having said that, some general trends can be observed. For example, noise increases with pipe diameter and blow energy [10].

The temporary pile driven at Pier 29 had an outer diameter of 75cm. Steel piles of 76cm diameter, diesel-driven, produced SPL_{Pk} = 208 dB re 1 μPa, *SPLrms* = 192 dB re 1 μPa and *SEL* = 180 dB re 1 μPa^{2}s at 10m range [11]. We measured SPL_{Pk} = 207 dB re 1 μPa, *SPLrms* = 194 dB re 1 μPa and *SEL* = 183 dB re 1 μPa^{2}s at 14m range--comparable.

The permanent pile driven at Pier 26 had an outer diameter of 150cm. A hollow steel pile of 168cm diameter, diesel-driven, was recorded at 4, 10 and 20m range; SPL_{Pk} was 219, 210 and 204 dB re 1 μPa respectively; *SPLrms* was 202, 195 and 189 dB re 1μPa [11]. We estimated a maximum SPL_{Pk} of 217 dB re 1 μPa and a maximum *SPLrms* of 201 dB re 1 μPa at 14m range for the end of the pile driving, which is comparable. A 160cm-diameter pile, driven with an 80-200kJ hammer and measured at 750m range, had *SEL* = 162 dB re 1 μPa^{2}s [10]. Our measurement at 750m was less possibly due to the high-loss environment in this shallow part of Moreton Bay.

Bioacoustic impact on marine fauna

There is limited knowledge of the effects of pile driving noise on marine life. The only damage that has ever been observed in any marine species as a result of near-by pile driving is lethal injury in fish [12,13]. The latter study was initially carried out by this author. The piles around which dead fish were seen were closed-end piles that were driven into rocky ground; a very different scenario. Post-mortems revealed haemorrhaging and burst swim bladders. Unfortunately, neither of these projects was able to produce any information on the sound metrics and thresholds responsible for the observed damage. A review of the available scientific information on bioacoustic impact on fish [11,14] led to the derivation of interim criteria for injury of fish exposed to pile driving [15]. For any single strike, a sound exposure level of *SEL* > 187 dB re 1μPa^{2}s and a peak sound pressure levels of SPL_{Pk} > 208 dB re 1μPa could cause injury.

No study to-date has shown injury in marine mammals from pile driving. However, data on temporary hearing loss (TTS: temporary threshold shift) after exposure to intense sound, including pulsive sound resembling seismic airguns, has been measured. After a major review effort, marine mammal noise exposure criteria were released [16]. Injury was understood as the onset of PTS (a permanent threshold shift) and extrapolated from TTS data. For PTS in cetaceans (whales, dolphins and porpoises) from single or multiple pulses, the threshold was SPL_{Pk} > 230 dB re 1μPa and *SEL* > 198 dB re 1μPa^{2}s (M-weighted [16]). A TTS in a mid-frequency cetacean was observed at SPL_{Pk} > 224 dB re 1 μPa and *SEL* > 183 dB re 1μPa^{2}s after exposure to a single pulse [17].

These levels were shown as horizontal straight lines in Figure 5. Looking at the SPL_{Pk} criteria, levels for the temporary pile were below all thresholds. The permanent pile was above the fish injury threshold over 40m range, but below the cetacean thresholds. *SEL* in Figure 5 were not M-weighted and are thus higher than if they had been weighted for mid-frequency cetaceans (M-weighting reduces the energy at frequencies below a few hundred Hz, where most of the pile driving energy is distributed.). The comparison with SEL criteria is thus "conservative". A single pulse from the temporary pile was below all thresholds; a single pulse from a permanent pile exceeded the fish injury threshold for ranges <25m and the cetacean TTS threshold for ranges <35m. Summing *SEL* over an entire pulse train (Figure 2b), yielded cumulative *SEL* that were 23 dB higher than single-pulse *SEL*, surpassing the cetacean PTS threshold over ranges <60m for the temporary and <100m for the permanent pile. It is unlikely that an animal would remain within close range for the duration of driving an entire pile. If an animal starts moving away after receiving one pulse, and given that received levels drop quickly with increasing range, the single pulse curves might be more applicable than the cumulative *SEL* integrated over an entire pulse train. There are no data on cumulative *SEL* thresholds for fish injury or cetacean TTS; the thresholds plotted are for single pulses only. It took less than 20 minutes to drive the recorded piles. If all went well, a maximum number of two temporary piles and one permanent pile were driven in one day, yielding a duty cycle (the ratio of pile driving noise being 'on' and 'off') of 60 min / 24 h = 0.04. It took a minimum of 24-28h before the next set of temporary piles could be driven, and at least a week in between permanent piles.

Moreton Bay has two resident dolphin species, both mid-frequency cetaceans, the bottlenose dolphin (*Tursiops truncatus*) and the indo-Pacific humpback dolphin (*Sousa chinensis*). Local residents and construction workers have reported sighting dolphins in the area throughout the year. However, we did not observe any animals within the vicinity of the piles during the recording, and a shut-down zone of 200m radius was scanned for cetacean presence as part of a monitoring and management plan, which J.F. Hull, Albem, the EPA and the Department of Main Roads had worked out. Elsewhere, harbor porpoises (*Phocoena phocoena*) avoided close ranges and responded to pile driving sound at ranges > 21km [18] from larger piles; however, received levels at these ranges were not reported.

We did not observe any dead fish close to the pile, nor did we see fish in abundant numbers here. It is possible that fish temporarily avoided close ranges to the pile; behavioural thresholds for fish require more research.

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REFERENCES

[1] Richardson, W.J., Greene, C.R., Malme, C.I., and Thomson, D.H. (1995). 'Marine mammals and Noise.' (Academic Press: San Diego)

[2] Blackwell, S.B., Lawson, J.W., and Williams, M.T. (2004). Tolerance by ringed seals (*Phoca hispida*) to impact pipe-driving and construction sounds at an oil production island. *Journal of the Acoustical Society of America* **115**, 2346-2357.

[3] Collins, M.D., Cederberg, R.J., King, D.B., and Chin-Bing, S.A. (1996). Comparison of algorithms for solving parabolic wave equations. *Journal of the Acoustical Society of America* **100**, 178-182.

[4] Zhang, Z. and C. Tindle. (1995). Improved equivalent fluid approximations for a low shear speed ocean bottom. *Journal of the Acoustical Society of America* **98**, 3391-3396.

[5] Hamilton, E.L. (1980). Geoacoustic modeling of the sea floor. *Journal of the Acoustical Society of America* **68**, 1313-1340.

[6] Perkin, R.G., and Lewis, E.L. (1980). The practical salinity scale 1978: Fitting the data. IEEE *Journal of Oceanic Engineering* **OE-5**, 9-16.

[7] Everest, F.A., Young, R.W., and Johnson, M.W. (1948). Acoustical characteristics of noise produced by snapping shrimp. *Journal of the Acoustical Society of America* **20**, 137-142.

[8] Readhead, M.L. 1997. Snapping shrimp noise near Gladstone, Queensland. *Journal of the Acoustical Society of America* **101**, 1718-1722.

[9] Au, W.W.L., and Banks, K. (1998). The acoustics of the snapping shrimp *Synalpheus parneomeris* in Kaneohe Bay. *Journal of the Acoustical Society of America* **103**, 41-47.

[10] 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. Cowrie Report ENG-01-2007.

[11] Hastings, M.C., and Popper, A.N. (2005). Effects of Sound on Fish. Report for Jones & Stokes, Sacramento, CA.

[12] Caltrans. (2001). Marine Mammal Impact Assessment: San Francisco – Oakland Bay Bridge East Span Seismic Safety Project; Pile Installation Demonstration Project. Report available from California Department of Transportation.

[13] Vagle, S. (2003). On the impact of underwater pile-driving noise on marine life. Fisheries & Oceans Canada Report.

[14] Popper, A.N., and Hastings, M.C. (2009). Review Paper: The effects of anthropogenic sources of sound on fishes. *Journal of Fish Biology* **75**, 455-489.

[15] Popper, A.N., Carlson, T.J., Hawkins, A.D., Southall, B.L., and Gentry, R.L. (2006). Interim criteria for injury of fish exposed to pile driving operations: a white paper. Available at http://www.wsdot.wa.gov/NR/rdonlyres/84A6313A-9297-42C9-BFA6-750A691E1DB3/0/BA_PileDrivingInterimCriteria.pdf [Accessed 1.7.2009].

[16] Southall, B.L., Bowles, A.E., Ellison, W.T., Finneran, J.J., Gentry, R.L., Greene, C.R., Kastak, D., Ketten, D.R., Miller, J.H., Nachtigall, P.E., Richardson, W.J., Thomas J.A., and Tyack P.L. (2007). Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. *Aquatic Mammals* **33**, 412-522.

[17] Finneran, J.J., Schlundt, C.E., Dear, R., Carder, D.A., and Ridgway, S.H. (2002b). Temporary shift in masked hearing thresholds (MTTS) in odontocetes after exposure to single underwater impulses from a seismic watergun. *Journal of the Acoustical Society of America*, **111**, 2929-2940.

[18] Tougaard, J., Carstensesn, J., Teilmann, J., Skov, H., and Rasmussen, P. (2009). Pile driving zone of responsiveness extends beyond 20 km for harbor porpoises (*Phocoena phocoena* (L.)) (L). *Journal of the Acoustical Society of America* **126**, 11-14.