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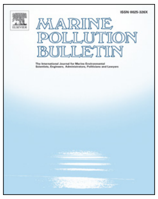

Underwater noise levels of pile-driving in a New Zealand harbour, and the potential impacts on endangered Hector's dolphins

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A R T I C L E I N F O

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A B S T R A C T

Impact pile-driving generates loud underwater anthropogenic sounds, and is routinely conducted in harbours around the world. Surprisingly few studies of these sounds and their propagation are published in the primary literature. To partially redress this we studied pile-driving sounds in Lyttelton Harbour, New Zealand, during wharf reconstruction after earthquake damage. That Lyttelton harbour is routinely used by Hector's dolphins (*Cephalorhynchus hectori*), an endangered species found only in New Zealand, provided further context for this study. Steel piles of 0.61 or 0.71 m diameter were driven using three different pile-drivers. Maximum calculated source SEL was 192 dB re 1 μPa^{2}s @ 1 m (SPL$_{0-p}$ of 213 dB re 1 μPa @ 1 m). Propagation of piling noise was strongly influenced by harbour bathymetry and a rock breakwater near the piling operation. We calculated range estimates at which Hector's dolphins may suffer temporary hearing threshold shift and behavioural change.

1. Introduction

Impact pile-driving produces impulsive, repetitive sounds that are among the loudest anthropogenic underwater sounds, particularly when steel piles are driven (Richardson et al., 2013). This form of noise pollution has been extensively studied in relation to windfarm construction (e.g. Bailey et al., 2010; De Jong and Ainslie, 2008; Nedwell et al., 2007) but there are very few studies of noise generated due to wharf construction that are published in the primary literature (for exceptions see Paiva et al., 2015; Würsig et al., 2000). Since several dolphin species routinely occur close inshore and in harbours (e.g. Dawson, 2018; Parra and Jefferson, 2018), this lack of literature is a potentially important weakness in the protection of these species.

Pile-driving noise has been established as a serious threat to some marine mammal species (Thompson et al., 2013). Wild harbour porpoise (*Phocoena phocoena*) show strong avoidance reactions to pile-driving (Brandt et al., 2011; Dähne et al., 2013; Tougaard et al., 2009). Temporary hearing loss has been documented in captive animals, following exposure to pile-driving noise (Kastelein et al., 2015). Hector's dolphin (*Cephalorhynchus hectori*), an endangered, nearshore delphinid found only in New Zealand, is routinely present in Lyttelton harbour. The Banks Peninsula Marine Mammal sanctuary (including Lyttelton harbour) was created in 1988 to reduce the impact of incidental catch in gill nets and trawling, the main threats to Hector's dolphins. That Hector's dolphins have very similar acoustic behaviour to harbour porpoises (Dawson, 2018; Dawson and Thorpe, 1990; Villadsgaard et al., 2007), are similarly sized and have broadly similar ecology (Würsig et al., 2018) raises the potential for pile-driving to be an additional impact, and provides the context for this study.

Impact pile-driving radiates noise into the water and sediment surrounding the pile. The majority of the underwater noise arises from radial expansion of the pile as it is struck by the hammer, radiating directly into the water column (Reinhall and Dahl, 2011; Tsouvalas and Metrikine, 2013). Energy is also transferred into the seabed, and can radiate back into the water, or travel as surface waves (Sholte waves) along the water-seabed interface (Tsouvalas and Metrikine, 2016a). For these reasons, pile-driving noise does not behave strictly as a “point” source. The spectrum of a typical pile strike is broadband, with most energy below 1 kHz but with significant energy extending to > 100 kHz, especially at close range (e.g. Nedwell et al., 2007; Tougaard et al., 2009).

Sound propagation is usually described as involving two kinds of losses, spreading losses and absorption. Spreading losses range between cylindrical (shallow water; 10*log(R), where R is range) and spherical (deep water; 20*log(R)). Absorption is frequency dependent, high frequencies are rapidly absorbed, while low frequencies can be detectable above ambient noise at very large ranges (Ainslie and McColm, 1998; Malme and Beranek, 1995). Shallow water, however, imposes a lower limit on the frequencies it can support to propagate based on depth (Forrest et al., 1993; Jensen et al., 2011). In practice, sound

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propagation is complex, especially in shallow water, influenced also by the roughness of the surface, depth, the nature of the bottom, and any layering in the water column (Marsh and Schulkin, 1962; Pine et al., 2014).

Modelling propagation from impact pile-driving presents an especially difficult challenge, due to the influence of bottom layer properties (Lippert and von Estorff, 2014) as well as bottom and surface reflections in shallow water transmission (Marsh and Schulkin, 1962). Currently there is no available software that can adequately model this complex process in a realistic coastal setting, accounting for the various environmental factors, and beyond ranges > 1.5 km (Denes et al., 2016; Duncan et al., 2010; Fricke and Rolfes, 2015; Reinhall and Dahl, 2011). For these reasons a strong empirical approach to measuring propagation was used in the present study.

The 2010 and 2011 Christchurch earthquakes extensively damaged the city's port in Lyttelton harbour. Port development was combined with repair work, under the Canterbury Earthquake Recovery Act (2011), allowing the work to be carried out without the usual resource consent process, and therefore, under less strict environmental management. The construction work involved 15 months of pile-driving.

Our purpose in this contribution is to describe the acoustic characteristics of noise pollution generated by impact pile-driving during the wharf reconstruction in Lyttelton harbour, quantify the propagation of this noise within this harbour, and investigate the potential impact this noise may have had on the local Hector's dolphin.

2. Materials & methods

2.1. Study area

Lyttelton harbour (43°36′47″S, 172°44′24″E), on the east coast of the south island of New Zealand, is a shallow harbour (Fig. 1) with a dredged shipping channel.

Pile-driving was carried out using three different impact hammers (Table 1). In each of these, hydraulic power was used to lift a steel hammer which then dropped via gravity on the top of the pile. The piles were steel, hollow, and closed-ended, with a diameter of 0.61 m or 0.71 m. Each pile was approximately 80 m long and driven an average of 66 m into the seabed (HEB construction, pers. comm. 2015). The contractor's records of pile-driving activity, which specified pile location, pile-driver, and the sequence of lift heights used, were made available by HEB construction and Port Lyttelton. A "soft start" using the hammer on its lowest energy setting for the first 2 min, was standard practice (i.e. required by the pile-driver manufacturers). Pile-driving was scheduled from Monday to Saturday between 7:30 am and 6 pm. Weather conditions restricted the actual operation time.

Table 1
Pile-drivers used in Lyttelton harbour.

Model	Gross weight (t)	Hammer weight (t)	Lift height range (m)	Max energy (kJ)
BSP 1146	35	14	0.5–1.5	206
Bruce SGH 1015	28	10	0.2–1.5	147
Junttan HHK18A	18	9	0.2–1.2	106

2.2. Field techniques and data collection

Sound recordings were made using three autonomous recorders (two DSG Ocean recorders and a SoundTrap HF) and two boat-based recorders (for recording locations see Fig. 1). The SoundTrap HF recorder (sampling frequency, f_s = 288 kHz, frequency response 20 Hz - 150 kHz ± 3 dB) was moored in an average water depth of 6.5 m, approximately 370 m from the piling activity ('SoundTrap' in Fig. 1). This location (close to the breakwater at 'Sticking Point') was chosen to reduce the risk of the recorder being damaged by docking vessels while minimising the range to the noise source. A DSG recorder (HTI-96 min hydrophone, f_s = 80 kHz, max. frequency response 2–30 kHz), was moored just outside the harbour channel, in about 8 m of water, directly in front of the piling 750 m away ('DSG' in Fig. 1). These two recorders were moored and removed each recording day. A further DSG recorder ('Duty cycle DSG' in Fig. 1) was set up on a duty cycle, recording for 5 min every hour (f_s = 80 kHz) and moored in about 9 m of water, continuously from February 27, 2015 to March 25, 2015, near a channel marker about 1.9 km from the piling activity. This recorder was used to record ambient noise. All autonomous recorders were moored about 2 m above the seafloor. Water height varied within 1.5 m due to tide (https://www.linz.govt.nz/). The substrate was generally a very fine clay silt mixture, including a small amount (1%) of sand, with a fluid mud layer on top (5–8 cm thickness, up to 45 cm in the channel), due to the high sedimentation in Lyttelton harbour (OCEL Consultants NZ Limited, 2014).

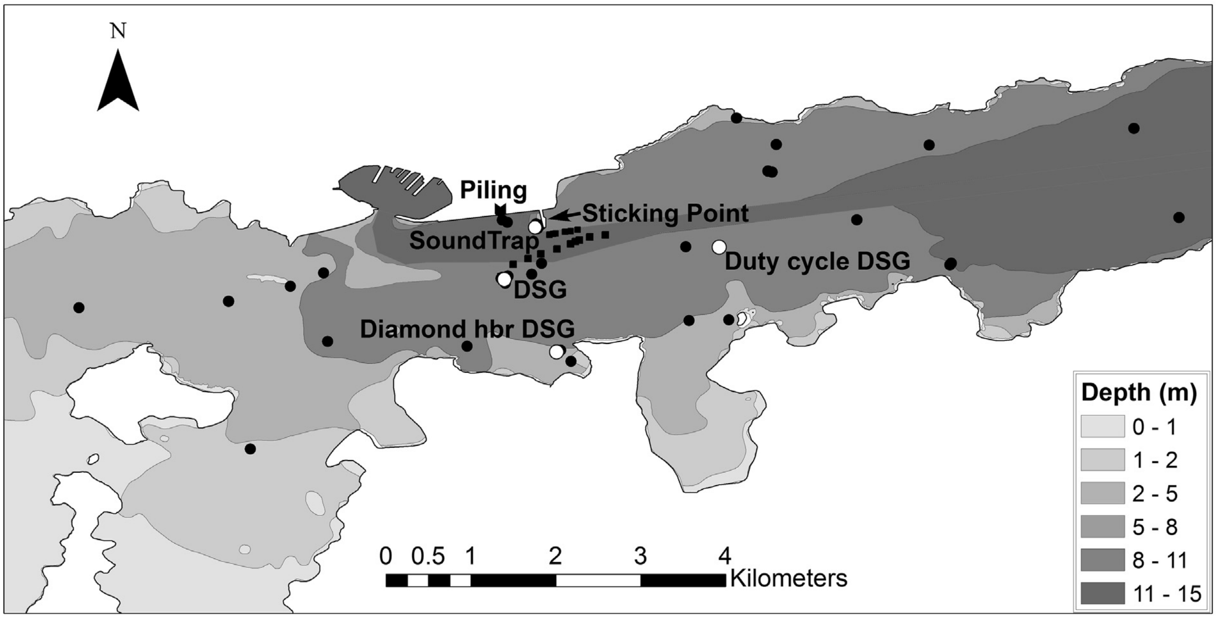

Fig. 1. Location of moored recorders (white dots) and boat based recordings (black dots) in Lyttelton Harbour.

Sound recordings were also made throughout the harbour at ranges of 92 m to 5.2 km from the piling, from an anchored or drifting 6.6 m research vessel (Fig. 1). For recordings beyond 400 m from the wharf, a sensitive, low-noise hydrophone specifically designed for measuring ambient noise (Reson 4032, Roland R-44 digital recorder, $f_s = 192$ kHz) was used.

To measure the broad spectrum of piling noise at close range (92–130 m) we used PAMGuard software running on a Laptop PC with a National Instruments 6351 A/D interface sampling at 500 kHz, with a Reson TC4013 hydrophone and VP2000 hydrophone amplifier. This hydrophone has a wider frequency response (20 Hz–170 kHz ± 3 dB) than the Reson 4032 (10 Hz–90 kHz ± 3 dB), and is better suited to recording very high signal levels due to its lower sensitivity.

Drift recordings enabled measurement of changes in pile-driving noise over small spatial scales, and were used to qualify the shadowing effect of Sticking Point. Distances from pile-driving were measured using a laser range finder (Leica Rangemaster 1000-R) and later compared to GPS locations recorded every 30 s on board the recording vessel.

All recording systems were routinely calibrated via a G.R.A.S. 42AA pistonphone (with appropriate couplers) with appropriate atmospheric corrections. All recordings were 16 bit. CTD (Seabird SB-19) casts were made at every recording location.

2.3. Sound analysis

Absolute sound levels were obtained using the pistonphone calibration tones on each recording. Calibration was carried out using the PAMGuide toolbox (from Merchant et al., 2015) in Matlab (Matlab 2014b, The Mathworks Inc.). The uncalibrated level a of the pistonphone tone at 250 Hz was determined using a power spectrum in PAMGuide (1 s Hanning window, 50% overlap). This was then compared to the known level b produced by the pistonphone (re 1 μPa: taking into account the effect of the couplers for each hydrophone) to produce a system sensitivity S:

$$S = b - a \tag{1}$$

S was then used as a correction factor for the corresponding recording.

Root mean square (RMS) broadband SPL is a useful metric to quantify an average level over a period of continuous noise (Merchant et al., 2015). An average level of ambient noise in Lyttelton harbour, was obtained close to the port, and at a location approximately in the centre of Lyttelton Harbour. Close to the port, we used recordings from the SoundTrap moored just inside Sticking point, and the DSG moored opposite the pile-driving (Fig. 1), gained on nine days between 4 January and 10 February 2015. From these recordings we calculated the overall RMS level for each day during the 30 min ‘smoko’ break in piling, and then took the median of those RMS values. In mid harbour, starting on 27 February, we used recordings from the duty-cycle DSG (Fig. 1), gained over a larger sample of days. For these recordings we calculated the RMS level over the entire record of 5 minute samples collected during the 26 day period it was moored in the harbour.

To analyse the noise from a particular pile-driver, hammer setting and pile location, a section which contained 10 strikes (as recommended by De Jong et al., 2011) was selected from the raw recording, avoiding flow noise, wave slap on the recording vessel and construction noise other than piling.

It has been shown that RMS level, a metric commonly used for measuring ambient noise, is not appropriate for transient signals such as a pile strikes (Madsen, 2005). The most widely used metrics for quantifying pile-driving noise are zero-to-peak Sound Pressure Level (SPL_{0-p}) and single-strike Sound Exposure Level (SEL), as defined in Southall et al. (2007). For transient signals, duration was defined as the ‘90% envelope’ (T_{90}) (Madsen, 2005).

All measurements were made via a custom written script in Matlab. First the script applied the correction factor S and filtered the signal using a 30 Hz digital highpass filter. This removed most of the noise due to water flow past the hydrophone and wave slap from the vessel and had negligible effect on piling noise, which contained very little energy below 30 Hz. A peak-finding algorithm (Yoder, 2009) was applied to the filtered signal. Power spectral densities (PSDs) and third-octave-band levels (TOLs) were calculated (with 1 s inter-strike-intervals) using the PAMGuide toolbox (Merchant et al., 2015). A 1 s Hanning window was used with 50% overlap for TOLs and PSDs.

2.4. Propagation measurement and modelling

Our aim was to create a strong empirical base of measurements from many locations throughout the harbour, using a simple propagation model to interpolate between measurement locations, and to extrapolate beyond them. A model is needed because it is difficult to construct a noise map only from measurements, as it is unrealistic to make recordings at all map locations in time short enough that none of the above variables change (De Jong et al., 2011). We aimed to find a propagation model that was as simple as possible while being sufficiently adaptable to represent important influences on the harbour's soundscape.

Statistical modelling (using general linear models) was used to determine which factors (‘energy’ - hammer energy (kJ); ‘pile driver’; (Bruce, BSP or Junttan); ‘stage’, stage of pile-driving (start, end or setting of pile); ‘row’, pile row on wharf (A–F); pile diameter (0.61 or 0.71 m); ‘pile ID’; ‘day’, date of recording) significantly influenced the received level of pile-driving noise, using recordings from the DSG location (Fig. 1). The best fitting model was determined by comparing AICc scores and using ANOVA (stats package, R Development Core Team, 2006) to test the significance of each term. Results were used to determine a subset of data representing the largest collection of recordings made under similar conditions. These were used for modelling propagation.

Measurements were made over an average of 10 strikes for the stationary recordings, and over single strikes for the drifting recordings (because range was changing). The latter data were weighted at 1/10th of the averaged measurements in the fitting procedure.

We assumed that bottom layer properties and sea surface roughness were constant over the data gathering period. Boat-based recordings were restricted to wind conditions below Beaufort 3, a wind range having negligible effect on sound transmission loss (Norton and Novarini, 1996) to at least 4000 m from the noise source.

In harbours, absorption, spreading losses, effects of depth, and bottom hardness can all contribute to propagation loss. Considering that most of the energy in pile strikes is at < 1 kHz, absorption has little effect (< 1 dB; Ainslie and McColm, 1998) on the broadband sound level over the ranges in this study (< 4 km), and spreading losses will be much more important. The shallow depth of much of the harbour strongly restricts propagation of low frequencies. The lower cut-off frequency for water of 6 m deep (over a sandy-silt bottom layer) is approximately 2000 Hz (Jensen et al., 2011; Shumway, 1960), meaning that little of the acoustic energy present in pile strikes was likely to propagate into the inner harbour. Additionally, the soft bottom layer gives poor reflection of the sound waves as they travel through the harbour leading to increasing loss with range (Jensen et al., 2011). Hence, the $-bR$ term (below) allows the model to reflect these losses as an effect that increases with range.

A model with source level (SL), geometric spreading coefficient (a) and absorption loss coefficient (b) was fitted to the dataset:

$$RL = SL - a\log_{10}(R) – bR \tag{2}$$

where RL is the received level (in dB re 1 $\mu Pa^2 s$) at range R (in meters) (Urick, 1983). Note that while absorption is heavily dependent on frequency, the absorption loss coefficient, b, in the propagation model (in dBm^{-1}) includes absorption across the entire frequency range of the pile-driving noise, not just a single frequency.

2.5. Noise map

Because source levels of pile strikes varied with pile-driver, pile location, substrate, penetration depth and hammer lift, we show propagation as a contour map of losses instead of absolute sound pressure levels. The fitted propagation model was used to generate a grid of ‘loss with range’ points spaced 0.005° in both latitude and longitude. Using the grid of losses enabled smooth interpolation between all recording locations. The grid was adjusted to integrate results of recording locations where there was no detectable change in pressure between ambient and piling noise in the waveform. In these cases it was often still possible to hear the pile-driving in the recording. To determine what propagation loss would be required for the piling noise be indistinguishable from ambient noise, the average ambient broadband SPL was compared to the average pile-driving source SPL_{0-p}. While there is no exact way to compare these rather different noise measures, this approach most accurately represents the decibel difference between the peak levels of pile-driving noise and the average ambient noise. This level was obtained by first determining an average level for the ambient broadband SPL. The overall average of the source SPL_{0-p} was derived by converting the modelled source SEL using the linear relationship between the measured data for these metrics.

Interpolation between loss points was calculated in ArcGIS (v10.3) using the local polynomial technique (with settings: polynomial order 2, smoothing factor 0.2 and an exponential kernel). To give more weight to the empirical measurements, the levels measured from point (averaged over 10 strikes) and drift recordings were weighted 100× and 10× higher, respectively, than the modelled grid points. The contours were drawn at 6 dB loss intervals, representing successive halving of sound pressure.

2.6. Impact zones

Recordings throughout the harbour were used to estimate ranges of Temporary Threshold Shift (TTS) onset. These estimates were based on previous studies of TTS in harbour porpoise. The “equal energy rule” is a useful concept as it includes both effects of noise amplitude and duration on TTS (Finneran, 2015). TTS onset in harbour porpoise, although dependent on a combination of duration and peak sound pressure levels of the noise, does not follow this rule (Mooney et al., 2009). Additionally, it is well known that the equal energy rule overestimates TTS for intermittent noise (Finneran, 2015). Hence, different ranges of impact are estimated based on different types of noise exposure. The relevant results used were: (1) TTS induced in a trained harbour porpoise after exposure to a single airgun pulse with an SEL of 164 dB re 1 $\mu Pa^2 s$ (Lucke et al., 2009); (2) TTS induced in a trained harbour porpoise after exposure to 1 h of played-back pile-driving noise (2760 strikes with an inter-pulse-interval of 1.3 s, with single-strike SEL of 146 dB re 1 $\mu Pa^2 s$; Kastelein et al., 2015); (3) a trained harbour porpoise exposed to a playback of pile-driving noise in a pool began to change its behaviour once the single strike SEL reached 133 dB re 1 $\mu Pa^2 s$ (Kastelein et al., 2013a; this threshold was estimated to be similar to what was observed in studies of wild harbour porpoise, Tougaard et al., 2009; Brandt et al., 2011; Bailey et al., 2010; Dähne et al., 2013) and (4) the maximum threshold level for detection of pile-driving noise in a trained harbour porpoise in a quiet pool was at a single-strike SEL of 75 dB re 1 $\mu Pa^2 s$ (Kastelein et al., 2013b).

3. Results

All platforms combined recorded a total of 147.5 h of underwater sound, of which 52 h were from the duty cycle DSG, 16.3 h were made on board the research vessel, and the remaining from the stationary DSG and SoundTrap. CTD casts made during the boat-based recordings indicated a well-mixed water column with a mean temperature of 19.0 °C (17.1–20.0 °C), and mean salinity of 34.1 PSU (33.3–34.3 PSU).

3.1. Ambient noise

Ambient noise levels measured over 26 days using the duty cycle DSG had a peak frequency around 300 Hz with a median PSD level around 60 dB re 1 $\mu Pa^2 Hz^{-1}$. The RMS broadband level over this period was 117.9 dB re 1 μPa, with 50% and 95% exceedence levels at 101.8 and 108.9 dB re 1 μPa, respectively. Recordings made during breaks in pile-driving showed highly variable broadband levels (96–146 dB re 1 μPa), and generally had most energy below 5 kHz. Median RMS broadband levels across this period were 119.2 dB re 1 μPa for the SoundTrap (50% and 95% exceedence levels at 112.4 and 101.1 dB re 1 μPa, respectively) and 119.6 dB re 1 μPa for the DSG (50% and 95% exceedence levels at 111.6 and 100.7 dB re 1 μPa, respectively) (average = 119.4 dB re 1 μPa).

3.2. Pile-driving noise

Over 92 days, pile-driving occurred on 46 days, with an average of 125.5 min of piling per day (SE = 16.7 min).

Recordings made at close range (up to 370 m) show strikes with high peak-to-peak SPLs and steep rise times (Fig. 2). The strikes are broadband with most energy present below 1 kHz, though some energy extends beyond 100 kHz (Fig. 3).

The maximum recorded level (averaging 10 strikes) had an SEL of 158 dB re 1 $\mu Pa^2 s$ and an SPL_{0-p} of 182 dB re 1 μPa at 370 m from the source. The fitted propagation model (see below) suggests that this would correspond to a point source SPL_{0-p} of 213 dB re 1 μPa @ 1 m.

All three drivers produced a similar distribution of energy across the frequency range: the highest energy was around 200–300 Hz, most energy contained between 50 Hz-10 kHz, but there was some energy to at least 100 kHz, particularly for the Bruce (Fig. 3).

Strike duration (T_{90}) varied between 59 and 624 ms. The longest durations occurred when the hammer was bouncing (Fig. 4), at the end of a piling sequence. Pile-driving stopped when pile movement was < 2.5 mm/blow on full power (D. Smith, HEB project engineer, pers. comm.). At this point the pile is considered to have hit solid substrate, and the elasticity of the pile causes the hammer to bounce. This produced the smaller secondary impulse closely following the main strike.

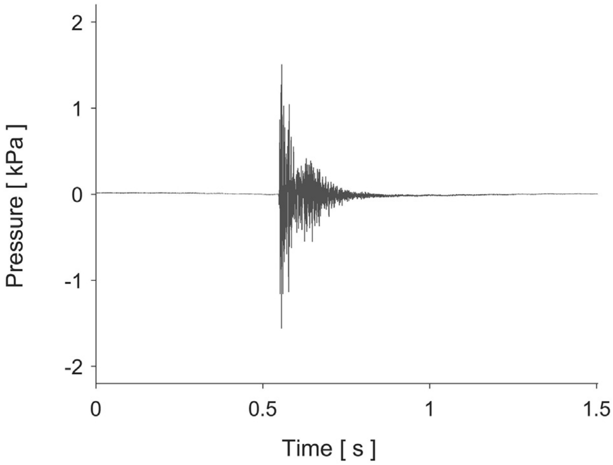

Fig. 2. Pressure waveform of pile strike, made by ‘Bruce’ hammer, recorded at 97 m from the pile-driving, frequency range 30 Hz–250 kHz (sampling rate 500 kHz).

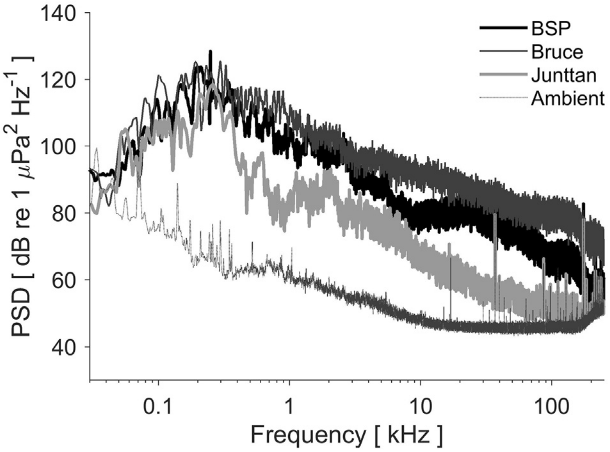

Fig. 3. Power spectral densities of all pile drivers and ambient noise, recorded at c. 100 m from the pile-driving, frequency range 30 Hz–250 kHz (sampling rate 500 kHz).

3.3. Statistical modelling

The formula of the GLM with the lowest AICc score, containing only significant terms (Table 2), was:

$$SEL \sim energy{*}pile\ driver + stage \tag{3}$$

The '*' indicates an interaction between the variables energy and pile-driver. It was concluded from this model that row, diameter, pile ID and day did not significantly influence the received SEL.

The subset of data used for the propagation modelling, therefore, included only recordings made from the Bruce or BSP hammer at the end stage of piling, at lift heights above 1.1 m. Since pile diameter was not a significant influence on the sound level here, the subset contained recordings from both pile sizes.

3.4. Propagation modelling

The measured pile-driving SEL decreased approximately logarithmically with distance (Fig. 5). The values obtained for the fitting parameters (Table 3) do not necessarily represent the physical properties in Urick (1983). In our case they are the simply the best fitting parameters to describe the combination of all the influences on transmission loss, not only geometric spreading and absorption in the water. It should be noted that while Eq. (2) could be fitted to pile-driving noise measurements in other scenarios, the fitted parameters apply only to the conditions in Lyttelton harbour, for the pile diameters and hammers described above.

Table 2
Parametric coefficients of terms in Eq. (3) fitted to pile-driving data using a GLM in R.

Parametric coefficients	Estimate	(95% confidence interval)	p-Value
Intercept	139.3	(138.2, 140.4)	$< 2 * 10^{-16}$
Energy (scaled), kJ	0.055	(0.036, 0.075)	$2.16 * 10^{-16}$
Stage: setting	−2.812	(−2.425, 1.180)	0.0191
Stage: start	4.996	(−10.790, −3.288)	0.0002
Pile driver: Bruce	−0.622	(−5.061, −0.564)	0.5029
Pile driver: Junttan	−7.039	(2.606, 7.386)	0.0007
Energy * Bruce	−0.002	(−0.038, 0.033)	0.8855
Energy * Junttan	0.116	(0.057, 0.174)	0.0004

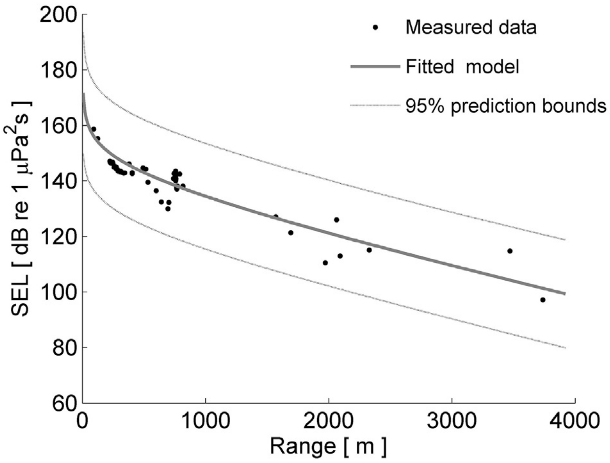

Fig. 5. Propagation model fitted with source level and the spreading and absorption loss coefficients as fitting parameters (adj. R^2 0.86).

Table 3
Fitted parameter values for propagation model (Eq. (2)) calculated using Matlab. Adjusted R^2 was 0.86.

Parameter	Predicted value (95% confidence bounds)
Source level	182 (167, 197) dB re 1 μPa^{2}s
a	12.6 (6.65, 18.6) dB
b	0.0095 (0.0071, 0.0118) dBm^{-1}

3.5. Noise map

A strike's SPL_{0-p} appeared to increase linearly with SEL, with the fitted relationship:

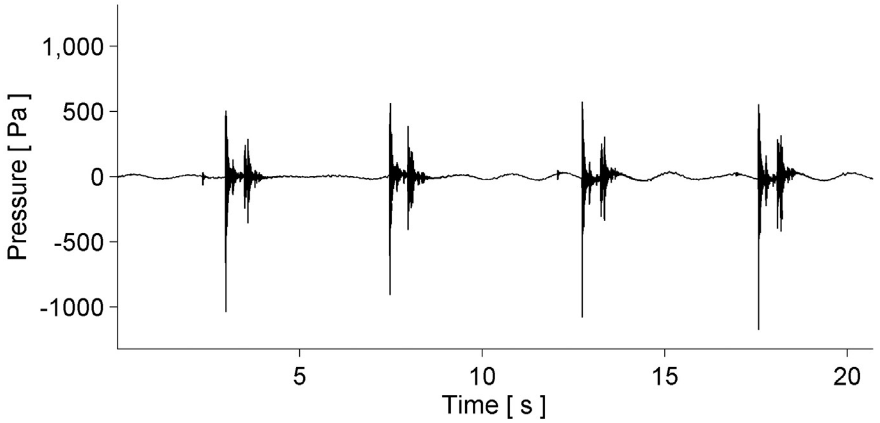

Fig. 4. Pressure waveform of BSP bouncing, end stage, lift height 1.5 m, on Jan. 27, 2015, frequency range 30 Hz–250 kHz, range to piling 103 m.

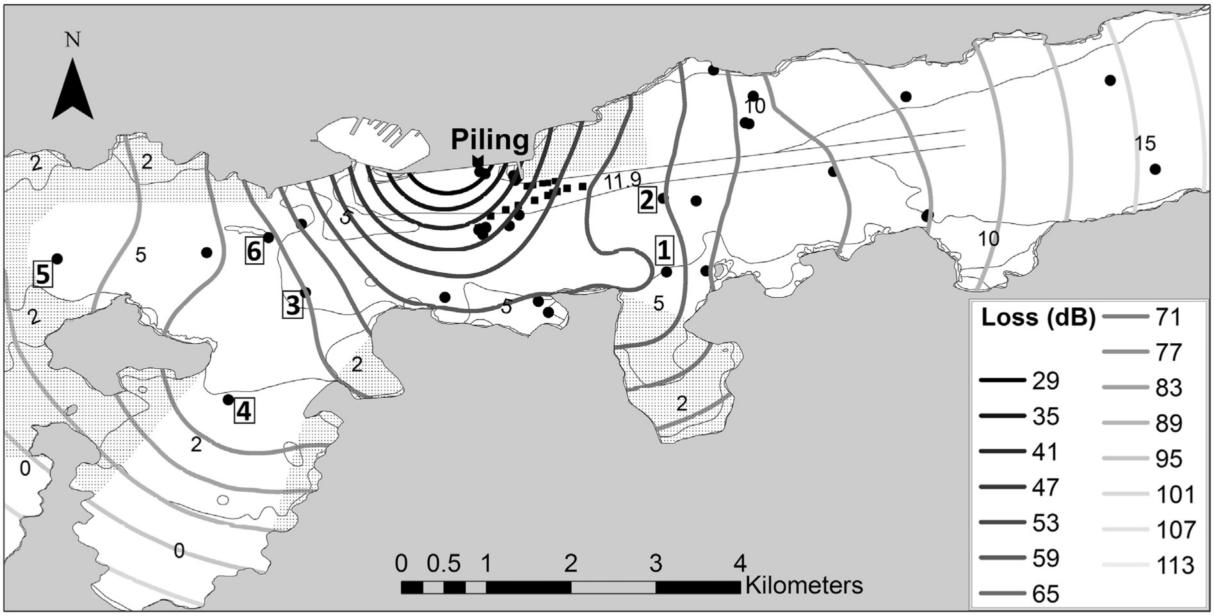

Fig. 6. Transmission loss contours in dB (thick, grayscale lines) are plotted over the harbour bathymetry (white fields numbered with maximum depth in m). Recording locations are indicated as black dots. The stippled areas indicate where the loss contours are likely unrealistic based on the fact that shielding will greatly increase the loss at these locations. Boxed numbers label specific recording locations for reference.

$$SPL_{0-p} = 0.95 \times SEL + 29.62, (R^2 = 0.95) \tag{4}$$

Using Eq. (4), a fitted source SEL of 182 dB re 1 μPa^{2}s corresponds to a source SPL$_{0-p}$ of 202.4 dB re 1 μPa. This is effectively what the average source SPL$_{0-p}$ of the Bruce or BSP driver would be, in the end stage of piling, if it behaved as a point source of sound. The difference between this and the average broadband RMS noise level (close to the port) is 202.4–119.4 = 83.0 dB. Modelled losses at grid points beyond where piling noise was measured to be indistinguishable from ambient noise were adjusted if necessary. If the loss at these points was $<$ 83 dB, indicating underestimation of loss by the model, the loss value was increased to 83 dB.

The non-circular contours (Fig. 6) indicate that the soundscape is strongly influenced by factors other than range. The most notable feature is the lower transmission loss towards location 1 compared to those shielded by Sticking Point (the breakwater to the east of the piling, see Fig. 1), for example location 2. The other interesting pattern on the western side is the large spacing in contours between locations 3 and 4. A possible explanation for this relatively low loss with range could be the shallowness of the water in this area, leading to cylindrical rather than spherical spreading.

Piling noise is very broadband at close range (Fig. 7a). Further away, both piling and ambient noise levels decrease. The recording at (b) was shielded by Sticking Point, which appears to have blocked most of the higher frequencies ($>$ 1 kHz) from propagating further (Fig. 7b). At location (c), almost 4 km away and in very shallow water, only the high frequencies persisted (Fig. 7c).

A breakwater (Sticking Point) present near the piling strongly influenced the propagation of the pile-driving sound (Fig. 8). SEL suddenly decreased as the drifting recording vessel passed Sticking Point (c. 526 m mark, Fig. 8), indicating a significant shielding effect.

3.6. Estimated zones of impact

3.6.1. TTS from a single pile-driving strike

Using a source level of 182 dB re 1 μPa^{2}s, our propagation data (Fig. 5) imply that an SEL of 164 dB (the level which induced TTS in a harbour porpoise after exposure to a single airgun pulse; Lucke et al., 2009) would occur in Lyttelton at a range of about 26 m from the pile-

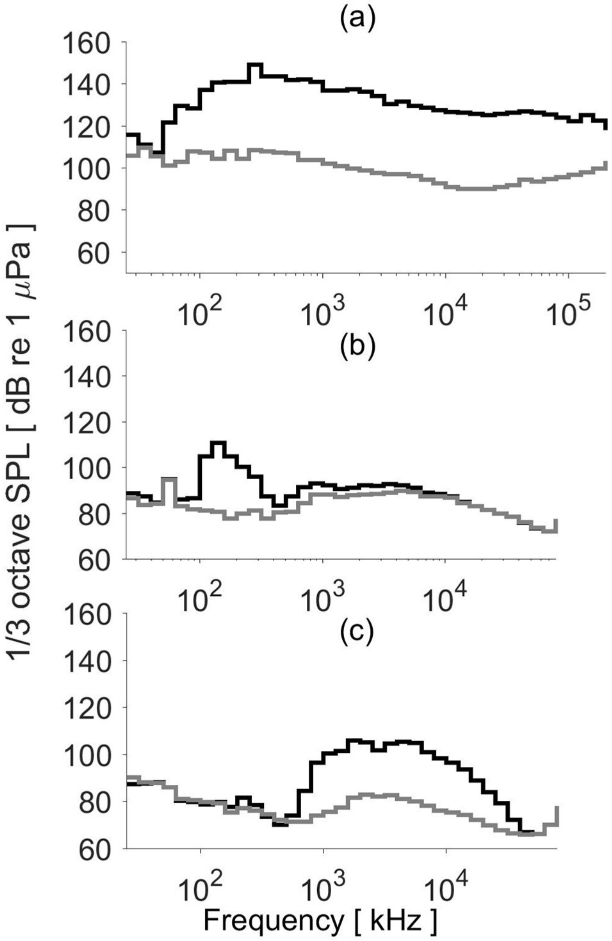

Fig. 7. Piling noise TOLs (black line) and ambient noise TOLs (grey line) measured at three locations around the harbour. (a): 100 m from piling, water depth 12 m; (b): at location 2 in Fig. 6, water depth 8 m, (c): at location 4, water depth 3 m.

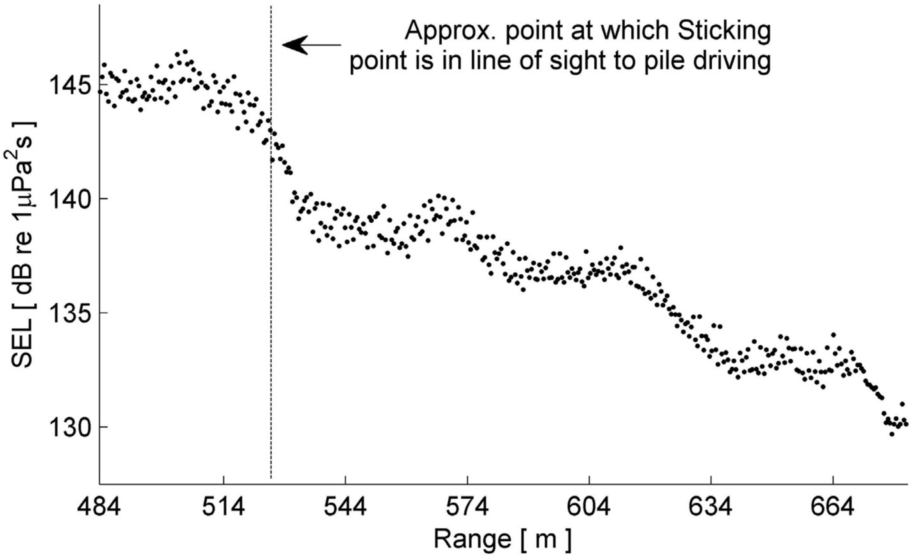

Fig. 8. SEL of each strike recorded while drifting past Sticking Point over a period of 11 min. Approximate range at which breakwater starts shielding pile-driving sound from the boat-based recording system is indicated by the vertical dotted line (526 m). Frequency range 30 Hz–96 kHz.

driving. Since this range is well within the near field of the pile-driving noise, it may not be reliably estimated. Because the hearing thresholds in that particular porpoise were considered to have been elevated (Lucke et al., 2009), this level should be considered a masked TTS. Hence, the range estimated at which TTS may occur in Hector's dolphin (with normal hearing thresholds) may be an underestimate.

3.6.2. *TTS from 1 h of exposure*

An SEL of 146 dB re 1 μPa²s (the single-strike level of pile-driving noise which induced a TTS in a harbour porpoise after 1 h of cumulative exposure; Kastelein et al., 2015) would occur at a range of about 376 m from the pile-driving. Using the map of loss contours (Fig. 6) this would occur at the loss contour of 36 dB and cover an area of approximately 0.38 km² (Fig. 9). The mean time between strikes was 1.3 s in the present study, but longer intervals (up to 4.5 s) were observed, particularly at the higher hammer lift-height settings (producing generally louder pile-driving noise). Since cumulative sound exposure level depends on the individual strike's SEL and the number of exposures (Southall et al., 2007), longer inter-strike-interval would require a longer period of exposure before inducing the same TTS.

3.6.3. *Behavioural change*

A captive harbour porpoise changed its behaviour when pile-driving noise was replayed at an SEL of 133 dB re 1 μPa²s (Kastelein et al., 2013a). In Lyttelton, this level would occur at a range of about 1120 m and at the loss contour of 49 dB (Fig. 9). Detection levels are, not surprisingly, much lower. A harbour porpoise could detect pile-driving noise in a quiet pool at an SEL of 75 dB re 1 μPa²s (Kastelein et al., 2013b). In Lyttelton this would occur at the 107 dB loss contour, well beyond the loss of 83 dB required for the pile-driving noise to be at the level of the average ambient noise. For the 5% most quiet times (in terms of ambient noise) in Lyttelton the pile-driving noise would then

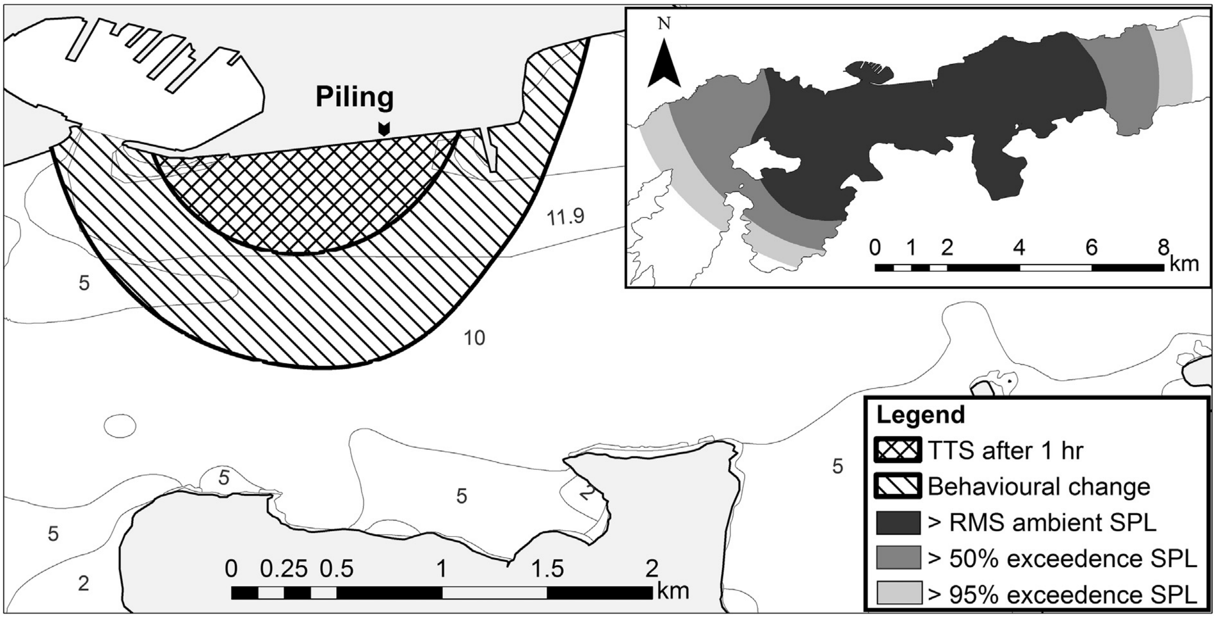

Fig. 9. Approximate zones in which pile-driving sound could impact Hector's dolphins. Inset: Increasingly lighter grey areas where pile-driving noise normally exceeds the RMS, 50% exceedence and 95% exceedence ambient noise levels, respectively.

be detected in an area up to 33 km^2 (see inset Fig. 9). However, for most of the time the ambient noise level is much higher, which will act to mask pile-driving noise and decrease the range over which pile-driving is detectable.

4. Discussion

Pile-driving introduced a large amount of noise into an already noisy harbour environment. Peak pressure levels were raised by over 1000 Pa (180 dB) (Figs. 2 & 4). At close range TOLs were raised by up to 45 dB across a wide frequency range (Fig. 7a), exceeding background levels 50% of the time over an area of up to 28 km^2.

There are surprisingly few peer-reviewed, published studies examining pile-driving in the context of wharf construction in harbours. An extensive set of measurements have been reported by the California department of transportation (Buehler et al., 2015), from many pile-driving projects, including a range of pile types and diameters. Most measurements were made in the near field and, therefore, are not directly comparable to our data from Lyttelton harbour (since measurements were only carried out in the far field). However, the SEL of 157 dB re 1 μPa^{2}s measured at 158 m, in water depth of 4 m, during bridge construction using 0.61 m diameter piles (no information on substrate or hammer energy), was similar to the modelled SEL of 153 dB re 1 μPa^{2}s at the same range in Lyttelton. The SELs at ranges of 260–340 m and 853–1530 m, in 0.9–9.1 m water depth, measured during wharf construction using 0.61 m diameter piles, were within 1 dB of the modelled levels in Lyttelton at these ranges. A more distant measurement at 2820–2922 m (SEL of 126 dB re 1 μPa^{2}s), was 15 dB higher than the modelled level in Lyttelton at this range, indicating that the transmission loss at this range was higher for Lyttelton. This is confirmed by the high absorption loss coefficient (Table 3), which is most significant at larger ranges.

Duncan et al. (2010) measured pile-driving noise in Port Phillip Bay, Australia, under very similar conditions to the pile-driving in Lyttelton. Pile type (diameter and material), hammer energy, and water depth were comparable to those in our study. The substrates in Duncan's study were silt layer on sand or sand on calcarenite, both layer types are much harder, with higher densities, than the mud/sand layer in Lyttelton. Comparing SELs at the same range from pile-driving shows that the levels measured in Lyttelton were lower by about 12 dB (Duncan et al., 2010). While the frequency content of pile-driving is relatively similar for most studies, the sound pressure levels recorded in this study are much lower than those of previous studies. Most studied much larger pile diameters, such as those used in offshore wind farms (for example Nedwell et al., 2007; Tougaard et al., 2009; Brandt et al., 2011), harder substrates (for example Nedwell et al., 2007; Robinson et al., 2007; Tougaard et al., 2009) and/or higher hammer energy (for example Lepper et al., 2009; Bailey et al., 2010; Brandt et al., 2011). Most studies were in much deeper water. Lyttelton Harbour is generally shallow; charted depths range from c. 13 m at the entrance to c. 5 m in front of the port, with an 11.9 m deep dredged channel allowing access for shipping. Our shallowest recordings were made in about 3 m of water. The shallowness of the harbour contributes to greater propagation loss for low frequencies.

The most comparable levels were recorded in the inner harbour of Fremantle, Australia (Paiva et al., 2015) where the SEL at 54 m was within 1 dB of our modelled level at this range. No information was available on hammer energy or pile diameter but since this harbour also experiences siltation (Paiva et al., 2015) the top layer of substrate is likely to be similar to the fluid mud layer in Lyttelton.

4.1. Propagation modelling

One of the more sophisticated attempts at modelling propagation of pile-driving noise in a harbour using freely available software (AcTUP v2.2L toolbox for Matlab; Collins & Porter, 2005; theory from Jensen et al., 2011), is by Duncan et al. (2010). This model considers spreading and absorption loss as well as influences of bathymetry and bottom layer properties. We attempted this modelling approach, and that of Marsh and Schulkin (1962), but the limited knowledge of Lyttelton's bottom layer properties and the model's high sensitivity to these inputs restricted the value of model outputs. Another approach, by Denes et al. (2016) used the parabolic equation method, but the model was validated at only two measurement locations and was likely inaccurate for ranges beyond those (> 1 km). Our approach was instead to develop a simple propagation model based on as much data as possible, referenced to measured pressure levels from multiple locations. The empirical data were weighted heavily in producing a contour map of losses (Fig. 6). The result is that the point recordings act to define the pressure levels, while the model interpolates between, and beyond them.

The geometric spreading coefficient of 12.6 was closer to cylindrical propagation (10) than to spherical propagation (20), most likely due to the shallow water depths in Lyttelton (3–13 m). Studies in deeper water show spreading losses of 20 (Bailey et al., 2010), 17–21 (Nedwell et al., 2007) and 16–29 (Blackwell, 2005). The absorption loss coefficient found in Lyttelton (0.0095 dBm^{-1}) is much higher than found in these studies, most likely due to a combination of higher absorptiveness of the soft bottom layers in Lyttelton and the shallower water depths in the harbour.

The noise map (Fig. 6) visualises how piling noise spread throughout the harbour. We think that this is an approach that should be used more. Further pile-driving is proposed in a planned expansion of the port of Lyttelton; this map provides useful information on how those sounds are likely to propagate. The contours, however, are approximations influenced by bottom layer properties, bathymetry and frequency content of the signal. Contour maps of underwater noise have been produced in previous studies (see for example (Cobo et al., 2007; Rossington et al., 2013) but to our knowledge none are based on the combination of modelled and empirical measurements. The map could be used for similar sources of anthropogenic sound near the wharf, so long as the source level is known, to estimate what sound levels would be received in different parts of the harbour. In particular, future studies of dolphin habitat use in Lyttelton Harbour may identify specific areas that are important (e.g. for foraging), in which the received noise level could be estimated. The accuracy of estimated levels will depend on how similar the frequency spectrum of the source is to the pile-driving noise used to develop the model.

4.2. Impact on Hector's dolphins

Hector's dolphins in Lyttelton harbour are routinely exposed to anthropogenic noise, particularly from small and large vessel traffic. Pile-driving noise had a much higher peak pressure, was impulsive, and was present for around 2 h (but up to 9 h) per day. It had the potential to impact Hector's dolphins in a variety of ways. If sufficiently close to the piling, Hector's dolphins could experience temporary hearing loss (Fig. 9), which could decrease their ability to forage via echolocation and detect environmental cues. It must be noted that the original recording of the pile-driving used in the playback in Kastelein et al. (2015) was made with a sampling frequency of 65 kHz therefore contained no frequencies above 32.5 kHz. Harbour porpoise hearing, however, reaches maximum sensitivity around 130 kHz (Kastelein et al., 2002) – frequencies that are certainly present in pile-driving strikes recorded at close range (e.g. Fig. 3; also see Dyndo et al., 2015 and Hermannsen et al., 2014 for impacts of low levels of high frequency noise on harbour porpoise). Also, Kastelein et al. (2015) replayed pile-driving sounds to a captive harbour porpoise at only one level (146 dB SEL re 1 μPa^{2}s), which was as loud as their equipment could produce, and found that this level caused TTS. It is possible that a lower level would have caused TTS also. It is important that 146 dB SEL re 1 μPa^{2}s is not to be regarded as the threshold at which TTS was induced.

The level at which TTS is induced also depends on the frequency of the sound, with a lower threshold for higher frequency sounds, following the harbour porpoise audiogram (Tougaard et al., 2015). Furthermore, this TTS was measured in one captive harbour porpoise, which may have a lower hearing sensitivity than wild harbour porpoise. The level found to induce TTS in Kastelein et al. (2015), therefore, is likely to underestimate the level at which TTS would occur in response to actual (as opposed to recorded then played back) pile-driving noise on wild harbour porpoise.

Pile-driving noise is unlikely to mask echolocation clicks, but has much more masking potential for environmental cues (e.g., from prey and predators) as these are at a much lower frequency than echolocation clicks, and pile-driving noise has much more energy in these frequency ranges.

Although reporting the details is beyond the scope of this paper, we made visual and acoustic observations which are relevant to the question of how dolphins responded to pile-driving sounds. Of 15 boat surveys in Lyttelton Harbour during this study, Hector's dolphins were seen on 13. Seven sightings were made within 500 m of the piling location, three of which were within 3–7 min of piling activity. On 10 days our SoundTrap HF recorder was moored inside Sticking Point, approximately 370 m from the piling location. Hector's dolphin sonar clicks were clearly evident in recordings made on eight of those 10 days. On five days dolphin clicks were recorded simultaneously with pile-driving strikes. Our experience suggests that to be recorded at all, dolphins would have had to be within c.200 m of the recorder. Taken together, these observations indicate that pile-driving did not prevent at least some Hector's dolphins from using the nearby area (i.e. within some hundreds of meters of the pile-driving).

We also had three echolocation detectors (v.5 T-PODs) moored in the inner, middle and outer harbour. Statistical modelling of dolphin detections during pile-driving showed a significant decrease in the inner harbour, closest to the pile-driving activity, with a concomitant increase in detections in mid harbour (which is shielded by Sticking Point). This is consistent with dolphins moving away from the area closest to the piling operations into quieter areas (Leunissen, 2017). These data indicate that pile-driving acted to reduce the foraging area available to the dolphins. If displaced far enough out of the harbour, risk of being caught in fishing nets could be increased (Forney et al., 2017).

Because the pile drivers in this study were much smaller than those used in construction of offshore windfarms, our estimated areas of audibility (33 km^2) and behavioural change (1.5 km^2) are much smaller than those measured for harbour porpoise in relation to offshore windfarms (e.g. c.15,000 and 1400 km^2 respectively; Bailey et al., 2010). Hector's dolphin is an inshore species, with individuals having very small home ranges (Rayment et al., 2009). The pile-driving occurred within a confined harbour environment. Together these features increase the likelihood that this pile-driving operation may have had a significant impact on the local Hector's dolphins.

NOAA and NMFS (2016) have recently provided recommendations on permanent threshold shift (PTS) and TTS thresholds for cetaceans classified as having low, mid and high frequency hearing. These thresholds are based on frequency weighting noise according to the inverse audiogram of representative species in each frequency group (Finneran, 2015). Based on the worst case scenario in Lyttelton (i.e. max. single-strike source SEL of 192 dB re 1 $\mu Pa^2 s$, 2700 strikes per hour, 9 h of piling per day) the 24-hour cumulative PTS onset isopleth would occur for Hector's dolphins at c. 1500 m from piling, and for TTS at 2700 m (average 440 m and 1400 m, respectively, based on single-strike source SEL of 182 dB re 1 $\mu Pa^2 s$, 2700 strikes per hour, with 2 h of piling per day).

While the proposed thresholds represent the current best science, there are issues that need to be addressed. The thresholds of impulsive sound for the high-frequency cetacean group (including Cephalorhyncids) are heavily based on the Kastelein et al. (2015) study, about which we have expressed reservations above. Due to the scarcity of relevant data to address such a wide range of marine mammal species exposed to a variety of sound sources, the usual standards for statistical robustness, particularly avoiding pseudo replication, were not always met, potentially introducing bias (Wright, 2015; Tougaard et al., 2015). There are also insufficient data to model recovery after TTS and, therefore, determine the intervening time necessary to treat multiple exposures as separate events (Finneran, 2015). This deficiency is clearly relevant for sounds which occur in bouts, such as pile-driving. Lastly, Hector's dolphin hearing has never been tested. While it is likely to be similar to that of harbour porpoise, the uncertainty associated with this assumption is potentially significant, particularly when the choice of weighting function is critical in noise regulation (Tougaard and Dähne, 2017).

Given the endangered status of Hector's dolphin it is imperative that additional threats, including those from noise pollution, are minimised. Bubble curtains can significantly reduce the noise radiated into the water column (Lucke et al., 2011; Nehls et al., 2016; Tsouvalas and Metrikine, 2016b) particularly when confined (e.g Buehler et al., 2015). For Lyttelton Harbour, however, significant re-suspension of sediment could breach a condition of the Coastal Permit, and therefore make bubble curtains an unlikely noise-mitigation option for future construction work. Another strategy for reducing noise pollution could be to employ screw-piling technology, rather than impact pile-driving, which produces significantly less underwater noise (Saleem, 2011).

Declarations of interest

None.

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