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MEASUREMENTS OF UNDERWATER PILING NOISE DURING NEARSHORE WINDFARM CONSTRUCTION IN THE UK: POTENTIAL IMPACT ON MARINE MAMMALS IN COMPLIANCE WITH GERMAN UBA LIMIT

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Offshore pile and conductor driving can potentially cause acoustic disturbance to marine mammals, such as cetaceans (whales, dolphins and porpoises), the odontocetes (toothed cetaceans) of which are particularly reliant on the underwater sound field for spatial orientation, navigation, prey capture, communication, and predator avoidance. Disturbance ranges from behavioural changes, masking of communication signals, and temporary or even permanent hearing loss. There is currently no specific legal noise threshold in UK waters, but the Marine Management Organisation (MMO) has stipulated the requirement for noise monitoring during pile-driving operations when some windfarms are constructed. Measurements presented in this paper were taken during nearshore pile driving in the UK from a support vessel located 750 m from each pile (wind-turbine foundation). Results were compared with a threshold issued by the German Federal Environment Agency (UBA). Noise levels beyond the measurement location were predicted using a numerical model. Comparing results with the Southall criteria (Southall, B. L., et al., Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations, *Aquatic Mammals*, **33** (4), 2007), the Joint Nature Conservation Committee (JNCC) 500 m exclusion zone offered protection for most of marine mammals during pile driving events in this particular case.

Keywords: Underwater piling noise, wind-farm, marine mammals, UBA limit

1. Introduction

The UK generates more power from offshore wind farms than any other country in the world [1]. This number is increasing such as Rampion Offshore Wind Farm [2], Dudgeon Wind Farm [3] and Race Bank Wind Farm [4], which will increase the amount of UK individual offshore wind turbines by 274 [2-4].

A potential consequence of these developments is an increase in exposure of marine mammals to potentially damaging anthropogenic noise, especially during the construction period. Construction of an offshore wind turbine involves the process of piling, which generates high levels of impulsive noise.

Noise levels generated are influenced by many factors, including pile size, hammer energy (driving power), and geological properties at the site. Previous measurements show that source level can be between 210 dB and 250 dB (ref. 1 µPa) [5]. Frequency content can be from as low as 1 Hz up to 100 kHz.

There are a range of effects that excess noise can cause depending on level and marine species in question. For example, Temporary Threshold Shift (TTS) is a result of excessive noise that causes an animal's hearing threshold to increase temporarily making it harder to hear. Permanent Threshold Shift (PTS) results in irreversible hearing loss. Non-physiological effects include, inter alia, behavioural changes, habitat avoidance, cessation of feeding, and increased swimming speeds, or indirect effects on their prey [6]. The level of noise that causes these behavioural effects is not clear entirely, and changes depending on the animal and its previous experiences with any particular type of noise [7]. High-level noise can also cause auditory masking, which could affect a cetacean's ability to navigate, detect predators, and communicate with others [8, 9].

There are several criteria developed by marine biologists to assess the potential impacts of underwater noise on marine mammals [7, 10]. Based on experimental studies, the Southall criteria [7] provide thresholds for different marine species, depending on source type (single pulses, multiple pulses, or non-pulses). For example, for cetaceans, TTS onset is stated to occur at 224 dB Sound Pressure Level (SPL) peak or 183 dB (Sound Exposure Level (SEL), and for pinnipeds in water 212 dB SPL peak or 171 dB SEL [7]. The Southall criteria are not legislation in the UK, yet compliance with such criteria is required increasingly in permit or licence conditions for marine-industry operations.

While noise monitoring is required during offshore construction work by many countries, only a few of them, including Germany, Belgium, and Denmark, have specified a threshold for the maximal noise level. The 'German Federal Nature Conservation Act (2010)', considers TTS in animals to be injury and states that noise levels must not exceed 160 dB (SEL) or 190 dB (peak-to-peak level) at 750 m from the piling site [11]. Belgium has an interim criteria stating that the noise cannot exceed 185 dB (zero to peak level) at 750 m away from the piling site. Belgium also enforces a seasonal restriction from May to August [12]. Denmark states that harbour porpoises must not be exposed to 183 dB cumulative SEL, although distance is unspecified. This noise limit is implemented with the assumption that, upon hearing the noise, porpoises will begin fleeing at 1.5 ms^{-1} [13].

In the UK, the Marine Management Organisation (MMO) follows the Joint Nature Conservation Committee guidelines [14]. These guidelines do not state noise limits, but they do require observation of marine mammals using suitably equipped and certified Marine Mammal Observer (MMO) personnel and techniques, and the use of appropriate Passive Acoustic Monitoring (PAM) equipment and trained operator personnel are recommended [14, 15]. Currently, the UK Government has not introduced legislation on noise limits for offshore construction work; however, operators are required typically to monitor noise levels for the first four piles and provide reports to the MMO as a license condition, and operators who exhibit best environmental practices are more likely to be issued licences in future.

2. Methodology

Underwater noise measurements were conducted from an offshore support vessel, anchored at a distance of 750 m away from each pile. The noise monitoring system diagram is shown in Fig. 1, and relevant equipment specifications are listed in Table 1. Two Reson hydrophones were used: 1) TC4014, covering a bandwidth of 15 Hz to 470 kHz, and 2) TC4034 covering a bandwidth of 1 Hz to 470 kHz. The TC4014 hydrophone included a pre-amplifier. Both hydrophones were configured with voltage amplifiers, band pass filters, and a Data AcQuisition (DAQ) sound card (NI USB-6251). The DAQ sound card was connected to, and controlled by, a PC (laptop). Data were saved onto hard drives. Measurements were carried out at ½ and ¾ of the water depth (about 6 m). For background noise measurements, signals were recorded over 24 hours at each fixed measurement point prior to the piling operation. For transient piling noise, signals were taken over the entire piling process. At each site, sound profile measurements of Conductivity, Temperature, and Depth (CTD) were undertaken at a sampling rate of 5 Hz.

Noise level indexes were calculated using the measured noise data, including SPL (RMS, 30 s averaging time), un-weighted peak-to-peak level and single transient SEL in the ⅓ octave band.

Simulation was then conducted to obtain the Transmission Loss (TL) by using an underwater noise propagation model, Kraken, which is based on normal mode methods [16].

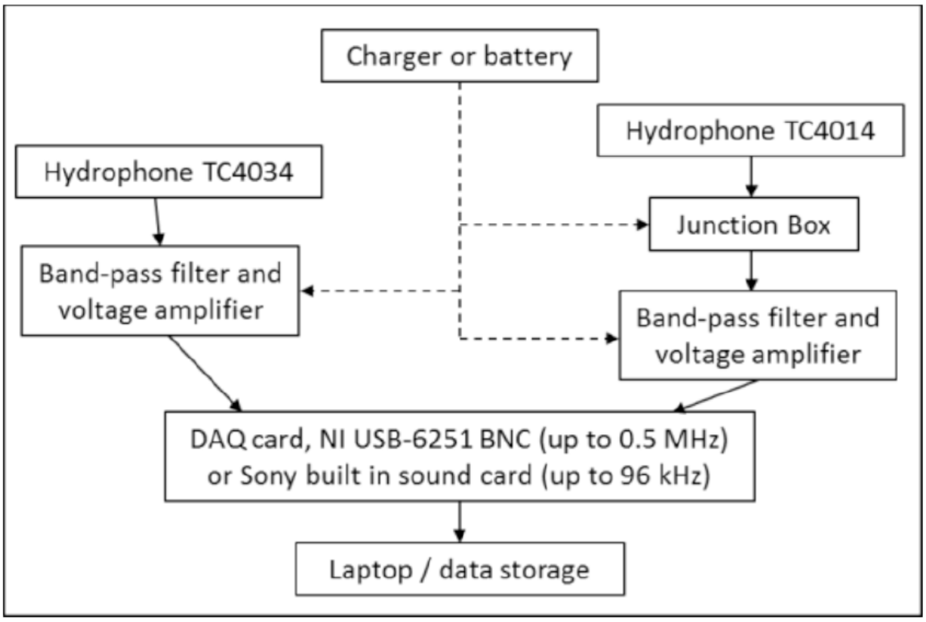

Figure 1: Noise measurement system.

Table 1: Noise measurement system specifications

Item	Specifications
Hydrophone TC4034	Receiving sensitivity: -211 dB re 1 V/µPa; linear frequency range: 1Hz to 470 kHz
Hydrophone TC4014	Receiving sensitivity: -186 dB re 1 V/µPa; linear frequency range: 15Hz to 470 kHz
Voltage amplifier and band-pass filter	Amplifier gain: 0 to 50 dB; band-pass frequency range: 1 Hz to 1 MHz
Junction box	Input connector: Jupiter Output connector: BNC
Battery charger	Input: 110/220 VAC Output: 15 V / 0.12 A
Battery	Output: 12 B / 0.12 A
NI DAQ card USB-6251 BNC	16-Bit, 1.25 Ms/s, 8 BNC analogue input; 2 BNC analogue output

3. Results and discussion

Measurements taken at two piles during the process are presented here. Noise was measured at two water depths; however, since the difference between these two depths is only ca. 1.5 m, difference between measured noise levels is minor. Consequently, only the noise level measured at ½ water depth is presented.

Compared to ambient noise level, the averaged root mean square (RMS) Sound Pressure Level (SPL) taken at ½ water depth were ca. 40 dB above background level for most frequencies, as shown in Fig. 2. Averaged Power Spectral Density (PSD) and SEL are shown in Figs. 3 and 4.

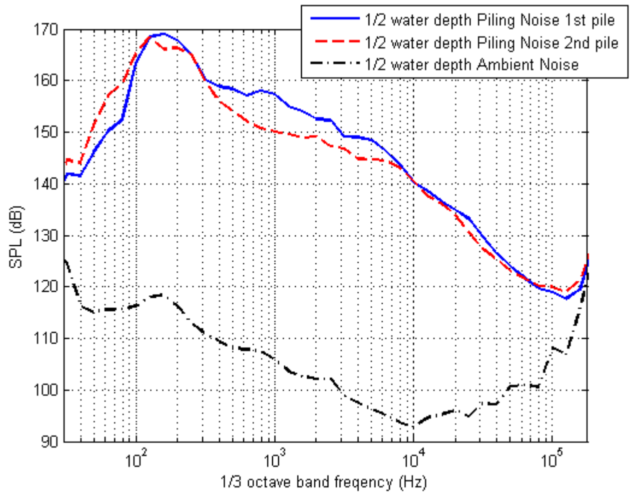

Figure 2: Averaged Sound Pressure Level (SPL), over the period covering 90% of the energy.

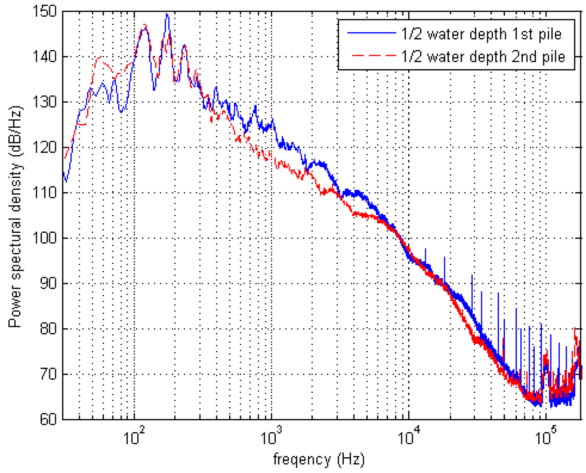

Figure 3: Averaged Power Spectral Density (PSD).

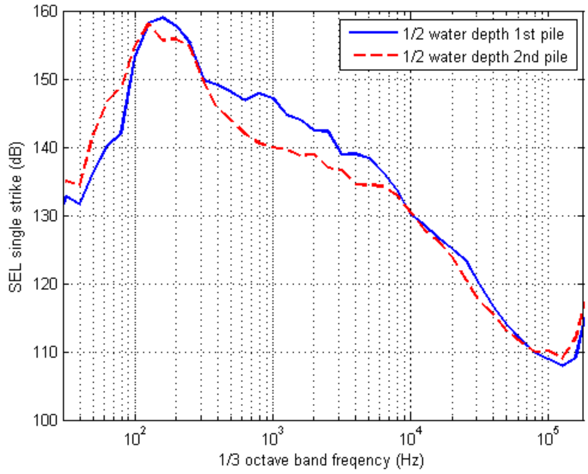

Figure 4: Averaged Sound Exposure Level (SEL), for single strike.

Figs. 2–4, show that the main energy of piling noise recorded was at frequencies up to ca. 30 kHz. According UBA's limits, overall SEL should be less than 160 dB and peak-to-peak level should be less than 190 dB at a range of 750 m from the site. These two levels were calculated and shown in Figs. 5 and 6.

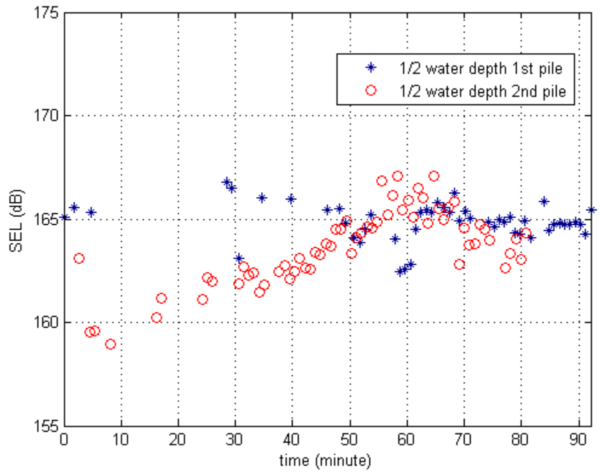

Figure 5: Sound Exposure Level (SEL) for single strike of piling noise against piling time, recorded at ½ water depth. Piling operations lasted ca. 92 minutes for the 1st pile and ca. 80 minutes for the 2nd pile.

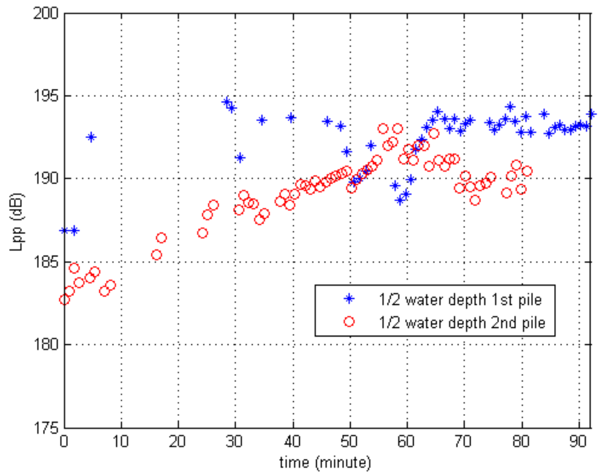

Figure 6: Peak-to-peak level (Lpp) for single strike of piling noise against piling time, recorded at ½ water depth. Piling operations lasted ca. 92 minutes for the 1st pile and ca. 80 minutes for the 2nd pile.

As seen from the figures, SEL for single strikes throughout the piling operation are nearly all larger than the 160 dB limit at 750 m; however, Lpp did not always exceed the 190 dB limit during the same period. In order to calculate SEL at ranges, Kraken underwater noise propagation models were used to provide TL. SEL at ranges were then obtained by subtracting TL from SEL measured at 750 m. Different weighting functions were used according to the Southall criteria [7]. Predicted SEL received by marine mammals during these two pile operations are shown in Figs. 7 and 8 respectively.

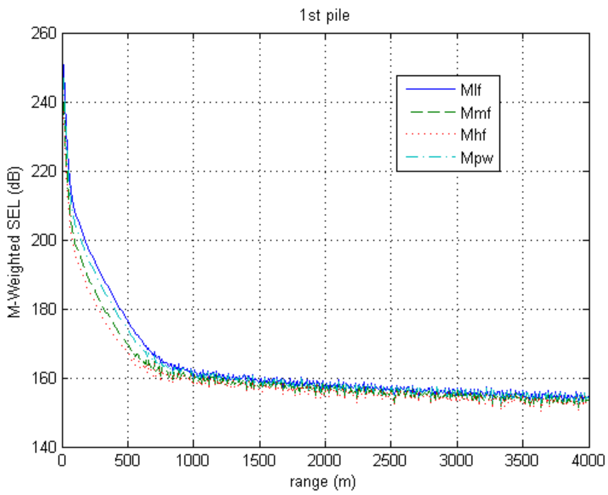

Figure 7: Predicted SEL for 1st pile over a range of 4 km, including different weightings for different marine mammals, M = marine mammals, Mlf = M-weighted low frequency, Mmf = M-weighted mid frequency, Mhf = M-weighted high frequency, Mpw = M-weighted pinnipeds in water.

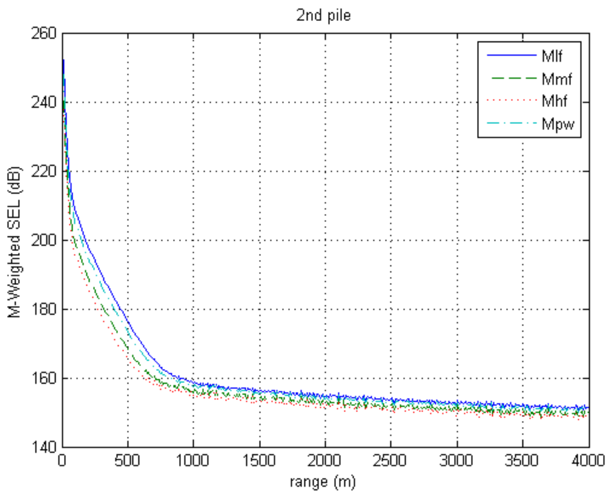

Figure 8: Predicted SEL for 2nd pile over a range of 4 km, including different weightings for different marine mammals.

Table 2: Potential auditory-impact ranges for the cetaceans and pinnipeds.

Marine Mammal Species	**Criteria**	**1st pile**	**2nd pile**
Cetaceans (Mlf) Low Frequency	PTS Auditory injury 198 dB re 1 μPa^2.s	200 m	200 m
Cetaceans (Mmf) Mid Frequency	PTS Auditory injury 198 dB re 1 μPa^2.s	110 m	120 m
Cetaceans (Mhf) High Frequency	PTS Auditory injury 198 dB re 1 μPa^2.s	90 m	90 m
Pinnipeds (Mpw)	PTS Auditory injury 186 dB re 1 μPa^2.s	310 m	320 m
Cetaceans (Mlf) Low Frequency	TTS onset cetaceans 183 dB re 1 μPa^2.s	400 m	400 m
Cetaceans (Mmf) Mid Frequency	TTS onset cetaceans 183 dB re 1 μPa^2.s	280 m	280 m
Cetaceans (Mhf) High Frequency	TTS onset cetaceans 183 dB re 1 μPa^2.s	240 m	240 m
Pinnipeds (Mpw)	TTS onset pinnipeds 171 dB re 1 μPa^2.s	560 m	540 m

Comparing predicted SEL in Figs. 7 and 8 to thresholds given by the Southall criteria [7], safe distances where the harbour porpoise and common seal would be unlikely to suffer from PTS and TTS are identified and listed in Table 2. From values presented in Table 2, aside from the potential TTS ranges for pinnipeds in water, ranges causing potentially PTS and TTS for both cetaceans and pinnipeds (for the two recorded piles) are all inside or around 500 m.

4. Conclusions

Background and piling noise was measured during installation of offshore-wind-turbine foundations to ascertain if noise produced complied with the German Federal Environment Agency (UBA) noise limits of 160 dB SEL and 190 dB Lpp at 750 m. Measurements were taken at ½ water depths during two piling operations. Measurements were modelled to predict how sound would propagate over larger distances. Noise exceeded the UBA's SEL limit at 750 m, but did not always exceed the Lpp limit.

SEL was calculated based on the measurement and numerical simulation. Comparing to the Southhall criteria [7], noise generated by the piling operation could potentially cause PTS and TTS for cetaceans and pinnipeds if they are within the JNCC 500 m exclusion zone [14]. Potential TTS ranges for pinnipeds are slightly larger than 500 m, as 560 m and 540 m for these two piles respectively. In light of these results, the JNCC 500 m exclusion zone offered protection for most of marine mammals during pile driving events in this particular case.

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