Underwater radiated noise due to the piling for the Q7 Offshore Wind Park

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The Q7 is the second offshore wind farm in the Dutch sector of the North Sea and, at 23 km off the Dutch coast, the world's first to be located outside the 12-mile limit. To support the wind turbines, monopiles, 54 metre long steel pipes with a diameter of 4 metres, are hammered into the seabed. The underwater radiated noise during the impulsive hammering of 9 out of 61 monopiles was measured. Although there is a wide concern about the impact of piling noise on marine life, there are no widely accepted criteria for the maximum acceptable noise levels. A quantitative comparison of the results of various reported studies is difficult, due to the lack of standardisation in the level definitions and data processing. The Q7 data have been analysed in terms of a broadband sound exposure level, peak pressure and pulse duration and a 1/3-octave band frequency spectrum of the sound exposure at different hydrophone locations, for each hammer stroke that has been recorded. The results are discussed in relation to the stroke energy, the hydrophone distance and depth and to proposed noise exposure criteria for marine mammals.

1 Introduction

There is an increasing concern for the impact of man-made noise on marine life [1,2]. The percussive piling for offshore installations is one of the stronger sources, together with explosions, seismic exploration and sonar operations. Previous studies suggest that the intense noise pulses generated by the piling are likely to disrupt the behaviour of marine mammals at ranges of many kilometres and have the potential to induce hearing impairment at close range [3]. However, a quantitative comparison of the results of various studies (e.g. [3-8]) in which the underwater noise from pile driving has been measured and reported is difficult, due to the lack of standardisation in the level definitions and data processing. Together with the still limited knowledge about the dose-response relationship for the various marine species, this hampers the development of noise exposure criteria. Recently, the *Noise Exposure Criteria Group* of the ASA has published 'initial scientific recommendations' for establishing marine mammal noise exposure criteria [9]. The acoustical terminology that is proposed in that publication gives a serious basis for standardisation.

For the analysis of the underwater noise that was measured during the construction of the Q7 Offshore Wind Park [10], we have followed a similar terminology. The underwater noise levels measured at various distances from the piling are compared with different noise exposure criteria.

2 Piling noise monitoring

The Q7 is the second offshore wind farm in the Dutch sector of the North Sea, at 23 km off the Dutch coast near IJmuiden. The local water depth is between 19 and 24 m. The sediment in the area contains mainly sand.

The monopiles for the Q7 off-shore wind park are 54 metre long steel cylinders of 4 m diameter and varying wall thickness, which are hammered approximately 30 m into the seabed, using 3000-4000 strokes in a period of 2-2.5 hours. The hammering was carried out from the '*Jumping Jack*' vessel of *Van Oord Dredging and Marine Contractors BV*, see Figure 1, using a *Menck MHU 1900S* hydraulic hammer.

The piling generally starts with a series of hammer strokes with increasing energy. Once the piling process is stable, the main part of the piling is carried out at a stroke energy of circa 800 kJ and a rate of 32 strokes per minute. An '*Ace Aquatec Silent Scrammer*' acoustic pinger, was used prior to the piling in order to deter marine animals from the piling area.

Figure 1 - Picture of the Jumping Jack piling platform (background) and of one of the measurement vessels

Underwater noise measurements were performed during the piling of 9 out of 61 monopiles. The measurements were carried out from two vessels, of which one remained stationary and the other was repositioned at various distances (between 0.4 and 5.6 km) during the piling of each monopile. Both vessels deployed an array of at least two hydrophones at different depths (types B&K 8101and 8103 and RESON TC4032 and TC4035). A weight of ca. 50 kg was added to the lower end of the cable to keep the array vertical. The hydrophone depths (between 3 and 15 m below the surface) are estimated on the basis of the cable length, assuming that the array was suspended vertically.

The complete set of raw data of all the measurements comprises a total of more than 30,000 noise events (piling strokes), measured with up to 8 hydrophones simultaneously. The data amount is ca. 125 Gbyte. With so much data available, a pre-selection of the data for analysis has been made. In order to give insight in the variability of the noise levels between two piles, the analysis is done for two monopiles, 2 km apart. The total number of acoustic pulses analysed is approximately 7,500.

3 Level definitions

The percussive piling produces a sound that is characterised by 'multiple pulses', in the terminology proposed in [9]. Each piling stroke produces an acoustic event, a pulse. In the received sound pressure at the hydrophone positions these events are separated in time and characterised by a strength and a duration. Both parameters require a clear definition, to avoid ambiguities. Our definitions are the same as those proposed in [9].

The ***peak sound pressure*** (***p_{peak}***) is defined as the maximum instantaneous unweighted sound pressure in a period of time *T*. To avoid ambiguity, we avoid the use of decibels (dB) for the peak pressure [11].

It is more robust to describe the 'strength' of a pulse in terms of a ***Sound Exposure Level*** **(*SEL*)** [9]. The *SEL* metric enables integrating the sound exposure over multiple pulses. The ***duration*** **(T_{90})** of the pulse is defined on the basis of the cumulative *SEL*. The T_{90} pulse duration is the period that contains 90% of the total cumulative energy in the signal, see Figure 2. The ***Sound Pressure Level*** **(*SPL*)** is defined as the dB-level of the average of the squared sound pressure, given in dB re 1 µPa. Note that the averaging time has a strong effect on the *SPL*-value for sound pulses.

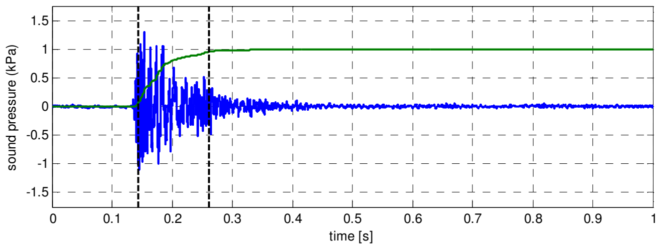

Figure 2 -Example of the acoustic pressure (bandwidth 3 Hz - 100 kHz) for a single stroke. The green line gives the cumulative energy, scaled to an arbitrary reference level. Vertical lines indicate the start and end times of the T_{90} duration.

At this stage, no frequency weighting is applied other than that due to the characteristics of the hydrophones and the recording system. The *SEL* per stroke is analysed in a proportional frequency bandwidth of one third of an octave.

4 Results

As an example of a result, the plots in Figure 3 give the sound exposure level (*SEL*), peak pressure (p_{peak}) and duration (T_{90}) per stroke as measured at a fixed position during almost two hours of piling.

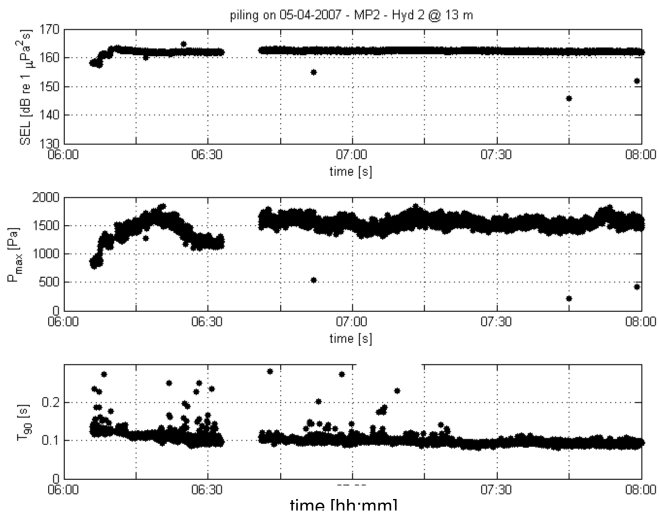

Figure 3 -The unweighted *SEL*, p_{peak} and T_{90} per stroke, at a fixed distance of 3.2 km. Each dot represents a stroke.

It can be seen that the levels are quite stable. The incidental deviating dots are due to misinterpretations in the automated processing of the data files. The stepwise increase in the energy per stroke at the beginning of the piling results in a stepwise increase of the *SEL* and peak levels. The unweighted *SEL* increases more or less linearly with the hammer stroke energy. A similar correlation was observed in [12] for piling in a chalk sea bed.

Figure 4 shows the 1/3-octave band spectra of the sound exposure level per stroke, averaged over a multiple of piling stroke pulses at the same energy, at 1.0 and 5.7 km from the piling. It is compared with the *SEL* of the average environmental noise in a 1 s window, prior to the piling at one of the locations. The piling noise is well above the environmental noise at the maximum measurement distance of 5.7 km. The main energy content of the noise is found in the range between 50 Hz and 1 kHz. It can be seen that the spectral content of the piling noise changes with distance. The loss of acoustic energy with distance is frequency dependent, showing higher losses at higher frequencies.

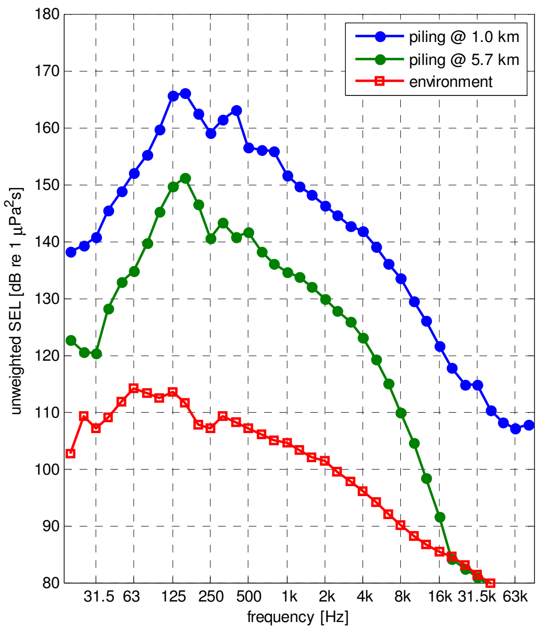

Figure 4 - The average 1/3-octave band spectra of the *SEL* at two different distances from the piling, compared with the *SEL* of the average environmental noise.

In Figure 5 a comparison is made between the averaged results of the analysis of the underwater noise due to the piling of the two selected monopiles. The unweighted *SEL* and p_{peak} measured at the various hydrophone locations are plotted against the distance. Only the results for hammer strokes at 800 kJ are selected for these plots.

It can be observed that both broadband noise level indicators decrease with increasing distance. The trend lines for idealised spherical spreading that are added in these plots suggest that the increase of transmission loss with distance can be described locally in terms of a simple power law. Note that this power law is only valid for the specific type of noise and the frequency bandwidth considered here, in the range of distances at which measurements have been done. An extrapolation of this trend towards larger or smaller distances and other frequency bandwidths is not allowed without further experimental evidence. The actual trend will be frequency dependent, see Figure 4.

Figure 5 also shows that the measurement results do not significantly deviate for the two different monopiles, nor for different hydrophone depths (between 8 and 15 m). The sound velocity was measured and found to be uniform across the water depth. No variation of the piling noise with penetration depth is observed for the piling in the Q7 environment. Apparently, the pile does not encounter the significant variations in resistance of the sediment, which can cause instabilities of the noise [12].

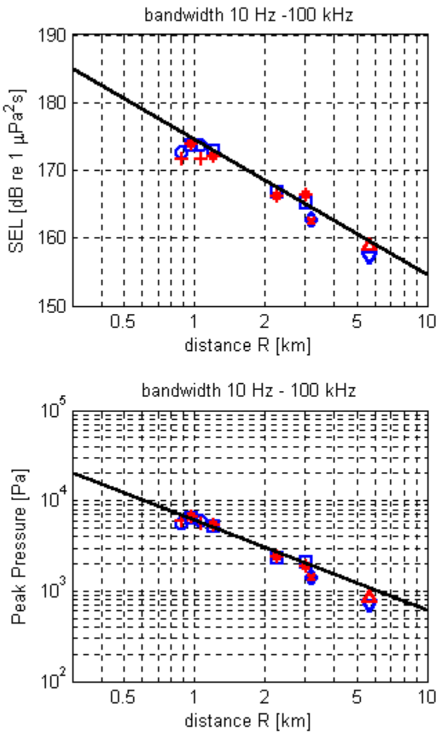

Figure 5 -The average unweighted *SEL* (top) and p_{peak} (bottom) per stroke as a function of the distance between the measurement position and the piling. The different markers refer to different hydrophone depths, the colour of the markers to the two different monopiles. The black lines are not fitted to the data but provided to indicate the local trend for the transmission loss due to spherical spreading.

5 Q7 piling noise compared with other studies

According to [3], the highest intensities recorded from a pile-driver gave a received *SPL* of 200 dB re 1 µPa (rms, averaged over a 10 ms pulse duration) at a range of 100 m. This corresponds with a *SEL* of 180 dB re 1 µPa^{2}s at 100 m. In [12] mean broadband *SEL*s are observed of 178 dB re 1 µPa^{2}s and 164 dB re 1 µPa^{2}s at ranges of 57 m and 1,850 m respectively, for piling at the same stroke energy (800 kJ) as in the Q7 wind park. The *SEL* measured at 1,850 m agrees surprisingly well with the *SEL* of ca. 164 dB re 1 µPa^{2}s that was measured at 1.8 km from the piling in the Q7 Park. Although the same stroke energy was used, there are significant differences between the two piling cases: Robinson has measured during the piling of a 2 m diameter, 65 m long test pile into a hard chalk sea bed in 8 to 15 m deep UK coastal waters, using a *Menck MHC*21 hydraulic hammer. Elmer et al [13] report measured underwater noise at a distance of 750 m from the piling for the *Amrumbank West* measuring mast to the North West of the island of Helgoland. The piling conditions for this 3.5 m diameter monopile in a water depth of about 23 m, with a stroke energy of 800 kJ, are very similar to the conditions for the Q7 park. The unweighted broadband *SEL* of 175 dB re 1 µPa^{2}s per stroke at 750 m reported for the *Amrumbank* monopile is in line with the observations for the Q7 piling Figure 5). The broad band peak pressure of 200 dB re 1 µPa (i.e. 10 kPa) at 750 m reported in [13] also agrees well with the levels observed for Q7 (Figure 5).

6 Example calculation of source level

The distance of our measurements from the monopiles is too large to permit a reliable estimate of source level from our data. As an alternative, we use the measurements of Robinson et al [12] at 57 m to estimate their source level [11], which, because of the use of the same pile driver at the same energy and the similar received levels at a distance of 1.8 km, is likely to be similar to Q7 source levels.

Robinson et al [12] observed an average (unweighted) *SEL* of 178 dB re 1 µPa²s at a distance of 57 m from the piling. According to the semi-empirical model of Marsh & Schulkin [14], in the frequency range 100 Hz to 10 kHz, propagation loss (*PL*) can vary between 28 dB re m² (for a sand seabed at 100 Hz) and 34 dB re m² (for sea state 3 at 10 kHz). A more precise calculation of *PL* is desirable; this calculation is intended as a rough estimate only. It is assumed that far-field conditions apply at the measurement distance. There is also a further uncertainty introduced by the accuracy of the model, which is estimated to be about 2-4 dB at short range, bringing the total uncertainty to about 4.5 dB.

The energy source level can be deduced [11] from:

$$SL_E = PL + SEL = 209 \text{ dB re } 1\ \mu\text{Pa}^2\text{m}^2\text{s} \pm 4.5 \text{ dB}. \qquad (5)$$

The corresponding source energy can be written

$$H = \frac{4\pi}{\rho_0 c_0} 10^{(\mathrm{SL_E} - 120)/10} \approx 7 \text{ kJ} \qquad (6)$$

(where $\rho_0 c_0$ [Ns/m^3] is the characteristic impedance of sea water), i.e. about 1% of the total hammer energy.

The theoretical upper limit on SL_E if all the 800 kJ hammer energy were converted to sound (and none into fixing the monopile into the ground) is 230 dB re µPa²m²s (Eq.6). If this energy were compressed into a time duration of (say) 10 ms, the source level based on RMS pressure would be 250 dB re µPa²m². Anything higher than this implies perpetual motion. Because most of the energy is not converted to sound, the true value is likely to be much smaller.

In order to get a feeling for the likely impact of the sound it is instructive to compute the mass of explosive charge required to release the same amount of acoustic energy as a single blow of a pile driver. A simple rule of thumb, based on Arons' measurements to a distance of 5000 charge radii [15], is that a detonation of one kilogram of pentolite releases approximately one megajoule of acoustic energy. Therefore 7 kJ corresponds to 7 g of pentolite. The average number of strokes required for a monopile in the Q7 Park is about 3500, which corresponds to a total acoustic energy of about 25 MJ, or 25 kg of pentolite. Allowing for the previously mentioned uncertainty in *PL*, this becomes between 9 and 70 kg of explosive in two hours.

7 Potential impact of the piling noise on harbour porpoises (*Phocoena phocoena*)

An assessment of the effect of noise exposure on marine animals requires a frequency weighting of the received sound to take into account the animals' hearing characteristics. Verboom & Kastelein [17,18] and Nedwell [6] propose to derive frequency weighting functions from the available audiograms, more or less similar to the derivation of the human A-weighting function. In [9] a more conservative set of M-weighting functions is proposed. These apply to five marine mammal functional hearing groups.

As an example, we consider the impact on harbour porpoises (*Phocoena phocoena*). These fall into the functional hearing group of 'high-frequency cetaceans' [9].

Figure 6 shows the results of applying the harbour porpoise weighting functions proposed in [9] and [17,18] to the measured *SEL* spectra. The legend gives the integrated SEL_W levels. The two different weighting functions lead to large differences in level and spectral content of the resulting sound exposure.

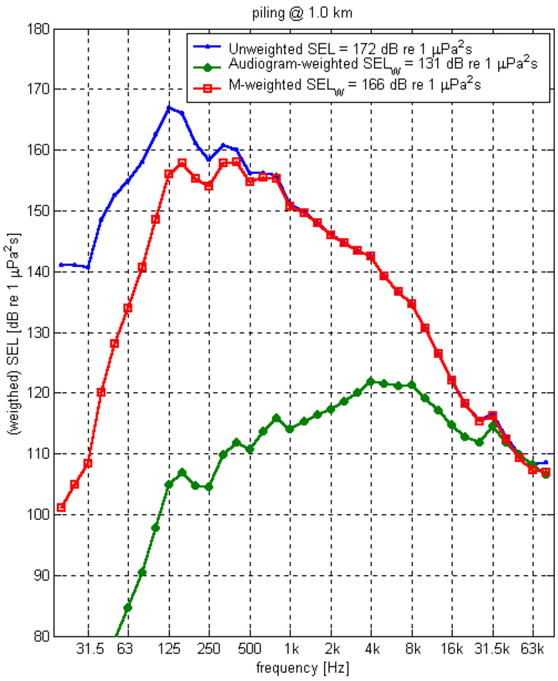

Figure 6 -The effect of the M-weighting for high frequency cetaceans [9] and the audiogram-weighting proposed by Verboom [18] on the *SEL* per stroke at 1 km distance.

In order to make use of the weighted noise level, it is necessary to apply noise exposure criteria based on the appropriate disturbance or damage thresholds. In [16] it is found that harbour porpoise discomfort thresholds are between 97 and 111 dB re 1 µPa unweighted *SPL*, for different narrowband communication signals in the frequency range between 10 and 14 kHz. In that frequency range, the average value of the hearing filter is about minus 10 dB. Consequently, the discomfort threshold is between 87 and 101 dB re 1 µPa weighted SPL_W. In addition to the measured discomfort threshold, the dose-response relationship for harbour porpoises (and harbour seals) has been estimated on the basis of an extrapolation of the thresholds for human hearing [16]. This leads to a SPL_W threshold for 'severe discomfort' at 125 dB re 1 µPa, for 'Temporary Threshold Shift' (TTS), at 137 dB re 1 µPa and for 'Permanent Threshold Shift' (PTS), at 180 dB re 1 µPa.

The averaged SEL_W values for each measurement are translated to weighted SPL_W, for a piling frequency of 32 strokes per minute at a constant piling energy of 800 kJ. These are plotted as a function of the distance to the monopile in Figure 7. All data appear to collapse within a relatively narrow band. The harbour porpoise weighting emphasises the high frequency noise, so that the SEL_W drops more rapidly with distance than the unweighted SEL (Figure 5).

It can be seen that the received SPL_W is well above the 'discomfort' threshold for the harbour porpoise up to the largest measurement distance (5.6 km). At distances smaller than about 1.5 km, the levels are above the 'severe discomfort' criterion and at distances closer than about 500 m, the levels are higher than the TTS criterion.

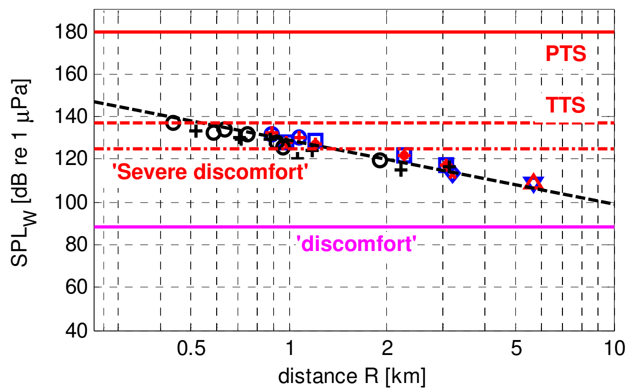

Figure 7 - The average sound pressure level during the piling (32 strokes per minute at 800 kJ), weighted with the harbour porpoise hearing filter [18], as a function of the horizontal distance from the monopile. Results of different hydrophones at different depths are all presented in the same figure. The black line is not fitted to the data but indicates a $-30\log_{10}(R)$ trend. The horizontal lines indicate the dose-response criteria proposed in [16].

In [9] noise exposure criteria are proposed for injury and discomfort in terms of the M-weighted SEL_W and the unweighted peak pressure. The 'multiple pulses' criteria for high frequency cetaceans apply to harbour porpoises. Any exposure in a series of pulses that exceeds the peak pressure injury (PTS) criterion (230 dB re 1 µPa, i.e. p_{peak}=316 kPa) is potentially injurious. The measured peak levels (Figure 5) are all well below this level. There are no data available regarding the recovery time of marine mammal hearing between pulses. As a precaution, the SEL_W criteria - of 198 dB re 1 µPa^{2}s for PTS and (implied) 183 dB re 1 µPa^{2}s for TTS - are applied to the total exposure due to all pulses in 24 hours. In practice, for the Q7 data this applies to the total exposure for a monopile. As a worst case, the total exposure is calculated for a fixed receiver position, ignoring the fact that it is unlikely that the animal will remain at the same position. The analysis of the noise recordings per stroke shows that the noise levels due to the piling of the monopiles for the Q7 Park are quite stable and that the results are very similar for different monopiles. The total weighted *SEL* at a single hydrophone position (at e.g. 1 km distance) due to the complete piling of a monopile can be estimated as follows: The observed M-weighted SEL_W at 1 km is 166 dB re 1 μPa^{2}s (±2 dB) per 800 kJ stroke (Figure 6). The average number of strokes required for a monopile in the Q7 Park is about 3500, of which 90-95% is performed at 800 kJ stroke energy. To estimate the total weighted sound exposure due to all strokes, $10\log_{10}(3500) \approx 35$ dB is added to the single stroke SEL_W, hence the total SEL_W at 1 km due to the piling of a monopile is circa 201 dB re 1 μPa^{2}s. This is 3 dB above the injury (PTS) threshold proposed in [9] and 18 dB above the (implied) TTS threshold.

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References

[1] W. J. Richardson, C. R. J. Greene, C. I. Malme and D. H. Thomson, 1995. *Marine Mammals and Noise*. San Diego, Academic Press

[2] L.S. Weilgart, *Can. J. Zool.* 85, 1091-1116, 2007: The impacts of anthropogenic ocean noise on cetaceans and implications for management

[3] P. T. Madsen, M. Wahlberg, J. Tougaard, K. Lucke & P. Tyack, *Marine Ecology Progress Series*, Vol. 309: 279–295, 2006: Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs

[4] S.B. Blackwell, J.W. Lawson & M.T. Williams, *J. Acoust. Soc. Am.* 115, 2346-2357, 2004: Tolerance by ringed seals (*Phoca hispida*) to impact pipe-driving and construction sounds at an oil production island.

[5] J.A. David *Water and Environment Journal* 20, 48-54, 2006: Likely sensitivity of bottlenose dolphins to pile-driving noise

[6] J.R. Nedwell, A.W.H. Turnpenny, J.M. Lovell & B. Edwards, *J. Acoust. Soc. Am.* 120(5), 2006: An investigation into the effects of underwater piling noise on salmonids

[7] J. Gabriel, T. Neumann, W.-J. Gerasch, K.-H. Elmer, M. Schultz-von Glahn & K. Betke, *Proc. German Wind Energy Conference DEWEK 2004*: Standards for the assessment of acoustic emissions of offshore wind farms

[8] D. de Haan, D. Burggraaf, S. Ybema, R. HilleRisLambers, *Wageningen IMARES report* OWEZ_R_251_TC 20071029, 2007: Underwater sound emissions and effects of the pile driving of the OWEZ windfarm facility near Egmond aan Zee

[9] B.L. Southall, A.E. Bowles, W.T. Ellison, J.J. Finneran, R.L. Gentry, C.R. Greene Jr., D. Kastak, D.R. Ketten, J.H. Miller, P.E. Nachtigall, W.J. Richardson, J.A. Thomas & P.L. Tyack et al, *Aquatic Mammals* 33(4), 411-521, 2007: Marine mammal noise exposure criteria: Initial scientific recommendations,.

[10] C.A.F. de Jong & M.A. Ainslie, *TNO report* MON-RPT-033-DTS-2007-03388, 2008: Underwater sound due to the piling activities for the Q7 Off-shore wind park

[11] M.A. Ainslie, *Proc. Acoustics'08*, 2008: The sonar equations: definitions, dimensions and units of individual terms

[12] S.P. Robinson, P.A. Lepper, and J. Ablitt, *Proc. IEEE Oceans 2007 - Europe*, 2007: The measurement of the underwater radiated noise from marine piling including characterisation of a "soft start" period.

[13] K.-H. Elmer, W.-J. Gerasch, T. Neumann, J. Gabriel, K. Betke & M. Schultz-von Glahn*, DEWI Magazin* Nr. 30, 33-38, 2007: Measurement and reduction of offshore wind turbine construction noise.

[14] H.W. Marsh & M. Schulkin, *J. Acoust. Soc. Am.* 34, 863, 1962: Shallow-water transmission

[15] A. B. Arons, *J. Acoust. Soc. Am.* 20, 343-346, 1954: Underwater explosion shock wave parameters at large distances from the charge.

[16] W.C. Verboom & R.A. Kastelein, *Proc. Undersea Defence Technology Conference*, Amsterdam, 2005: Some examples of marine mammal discomfort thresholds in relation to man-made noise

[17] R.A. Kastelein, W.C. Verboom, M. Muijsers, N.V. Jennings & S. van der Heul*, Marine Environmental Research*, 59, 287-307, 2005: The influence of acoustic emissions for underwater data transmission on the behaviour of harbour porpoises.

[18] W.C. Verboom, 2008, private communication