Chapter 92
Noise Mitigation During Pile Driving Efficiently Reduces Disturbance of Marine Mammals

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Abstract Acoustic monitoring of harbor porpoises (*Phocoena phocoena* L., 1758) indicated a strongly reduced disturbance by noise emitted by pile driving for offshore wind turbine foundations insulated by a big bubble curtain (BBC). This newly developed noise mitigation system was tested during construction of the offshore wind farm Borkum West II (North Sea). Because porpoise activity strongly corresponded to the sound level, operation of the new system under its most suitable configuration reduced the porpoise disturbance area by ~90%. Hence, for the first time, a positive effect of a noise mitigation system during offshore pile driving on an affected marine mammal species could be demonstrated.

Keywords Big bubble curtain • Sound exposure level • Noise pollution • Offshore wind farm • Harbor porpoise *Phocoena phocoena*

1 Introduction

Against the backdrop of an increasing utilization of offshore wind energy (Mann and Teilmann 2013), noise protection is an important issue because underwater pile driving during the founding of offshore wind turbines (wind energy areas [WEAs]) comes along with strong noise emissions causing disturbance and potential injury to marine mammals. To deal with this situation until now, different kinds of noise mitigation systems were developed and evaluated according to their noise mitigation

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potential (e.g., Würsig et al. 2000; Illingworth and Rodkin 2007; Nehls et al. 2007; Griessmann et al. 2010; Stokes et al. 2010; Koschinski and Lüdemann 2011; Wilke et al. 2012; Rustemeier et al. 2012a, b; Spence and Dreyer 2012; Bureau of Ocean Energy Management 2013).

Within the framework of the project HYDROSCHALL-OFF BW II (Pehlke et al. 2013), a new noise mitigation system, a prelaid big bubble curtain (BBC), was developed and its consequences for the presence of the harbor porpoise (*Phocoena phocoena* L., 1758) was tested during pile-driving activity for the offshore wind farm Borkum West II (TRIANEL WINDKRAFTWERK BORKUM GmbH & Co.KG) in the German Bight (North Sea).

In the southern North Sea, harbor porpoises are the most common marine cetaceans (Gilles et al. 2009) potentially prone to noise pollution by pile driving (e.g., Brandt et al. 2011; Dähne et al. 2013). These animals orient themselves acoustically by emitting high-frequency click sounds. For the protection of this and other species listed in the EC Habitats Directive (European Commission 1992), the German Federal Maritime and Hydrographic Agency (2010) and the German Federal Environment Agency (2011) imposed restrictions according to noise protection norms (160 dB_{SEL} [sound exposure level] and 190 dB_{Lpeak} [peak level] at 750 m distance from the sound source), supporting the further development of effective noise mitigation systems in German waters.

Positive effects of noise mitigation systems on marine mammals were not yet demonstrated under real offshore conditions, a situation that was changed by this study.

2 Materials and Methods

The wind farm Borkum West II, positioned 45 km north of Borkum Island (North Sea), consists of 40 wind turbines (40 more WEAs are planned for the future) and a transformer station. During foundation work for the WEA tripod constructions, 120 piles were driven into the sediment by a hydraulic hammer. The tested noise mitigation system, a BBC developed by HYDROTECHNIK Lübeck GmbH, consisted of jet nozzle hoses into which compressed air was pumped. The prelaying principle of the BBC, i.e., circular deployment of the nozzle hose(s) around the planned position of a turbine foundation before arrival of the jack-up vessel and then connecting and operating the hose after the jack-up vessel was positioned, was successful in causing no delays for the process of wind farm construction. The special configuration BBC 2, which was used here for certain analyses, consisted of a circular single hose of 560 m length, with small nozzles (1.5 mm) at a short distance from each other (30 cm).

Within the project, extensive data from 26 C-POD positions covering different distances between 0.4 and 36 km from the piling location and up to four hydroacoustic points of measurement were available (Pehlke et al. 2013), adding up to a worldwide exceptional data pool for investigating the response of harbor porpoises to underwater sound originating from noise-mitigated and uninsulated pile driving. Noise levels during ramming activity were standardized to a distance of 750 m from the sound source.

Detection rates of harbor porpoises according to pile-driving activity were assessed on a temporal scale of hours (PPM/h). Original PPM/h values were converted into modeled values (linear mixed-effects [LME] model) to account for random effects of different WEA and C-POD stations as well as for C-POD sensitivity differences. Due to a left-skewed distribution of converted PPM/h values and the presence of zero inflation (48% zero values in the dataset), the new parameter δPPM/h was derived from PPM/h by the following standardization procedure. Average detection rates from a period of 9 h before ramming (full hours $T_{-10\ h}$ to $T_{-2\ h}$), under the condition that no ramming took place in the preceding 24 h (until $T_{-34\ h}$), were assumed to be uninfluenced by pile-driving activity and are defined as the reference parameter PPM·s. The standardized parameter δPPM/h was defined as the difference between PPM/h values obtained during pile-driving activity and the reference parameter: δPPM/h = PPM/h − PPM·s. If δPPM/h < 0, then the detection rates during ramming activities were lower than the reference value before pile driving.

3 Results

The BBC configuration BBC 2 (circular single hose with small nozzles at a short distance to each other) under a full air supply of 0.32 m^3 air/(min · m hose) turned out to be the best compromise of efficiency and practicability under offshore pile-driving conditions. Its noise mitigation effect ranged between 9 and 13 dB (mean 11 dB) for the 50th percentile of the SEL (SEL50) and between 10 and 17 dB (mean 14 dB) for the peak level, which was rated to be efficient. Noise mitigation of a BBC 2 worked best at higher frequencies (Fig. 92.1).

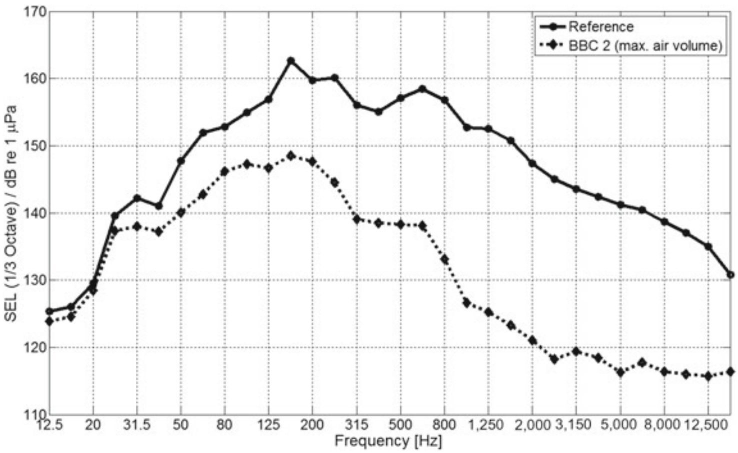

Fig. 92.1 Third-octave spectra of the standardized (750 m distance) single-event level during reference rammings (without noise mitigation system) compared with rammings insulated by a big bubble curtain (BBC) 2 configuration (circular single hose with small nozzles at a short distance to each other under maximum air supply), demonstrating the good noise mitigation of a BBC 2, particularly at higher frequencies. *SEL* sound exposure level. Values are means

Table 92.1 Dataset available for the analyses of the effect of different pile-driving sound levels on harbor porpoise activity

Sound level, dB_{SEL50}	No mitigation	BBC 2	BBC 1	Other
<135	60	266	120	83
135–140	57	206	118	130
140–145	195	135	84	57
145–150	237	33	58	76
150–155	147	31	12	26
155–160	92	6	14	28
>160	57	0	0	5

dB_{SEL50}, Sound level at 50th percentile of sound exposure level; BBC 2, big bubble curtain configuration with a circular single hose with small nozzles at a short distance to each other under maximum air supply; BBC 1, BBC configuration with hose with bigger nozzles at larger distance to each other compared with BBC 2; other, other BBC configurations. Available data had to include acoustic data and corresponding detection rates. Note the good noise mitigation of the BBC 2. See also Fig. 92.2 and Table 92.2

A possible effect of ramming noise pollution at different sound levels (5 dB_{SEL50} classes) on harbor porpoise detection rates was investigated over a dataset that had to include acoustic data and PPM/h rates of pile-driving activities insulated by different BBC configurations as well as without noise mitigation (Table 92.1).

Detection rates (PPM/h) during pile-driving activity were compared with those in a reference period before rammings. The standardized parameter δPPM/h described the amount of the effect (see Section 2). A strong correlation of increasing disturbance of harbor porpoises with increasing sound levels of pile driving (the latter corresponding to shorter distances from the sound source under similar noise-mitigating conditions) was uncovered (Fig. 92.2). The limit of a disturbance effect on harbor porpoises ranged between 140 and 145 dB_{SEL50}. From 145 dB_{SEL50} upward, a significant disturbance effect occurred (Table 92.2). The lowest porpoise detection rates were found for sound levels >160 dB_{SEL50}, tantamount to an almost total expulsion of animals. However, with the dataset available for the analysis of the sound level dependence of detection rates, those sound levels were not reached under the operation of a BBC 2 (Table 92.1), underlining the substantial noise-mitigating effect of this BBC configuration. Pointing in the same direction, at other sound levels causing a significant disturbance effect on harbor porpoises (down to 145 dB_{SEL50}), only few data were available when a BBC 2 was active (Table 92.1).

Combining both results, the considerable noise mitigation by a BBC 2 (Fig. 92.1), and the sound level-dependent disturbance effect on harbor porpoises (Fig. 92.2), logically induces a reduced disturbance of harbor porpoises during pile driving under noise mitigation by BBC 2, which could be further specified. Based on a sound propagation function established during the project (Pehlke et al. 2013), a theoretical distance to a sound source of known intensity was computable. For harbor porpoises, a radius of disturbance of ~15 km was obtained for uninsulated pile-driving activities.

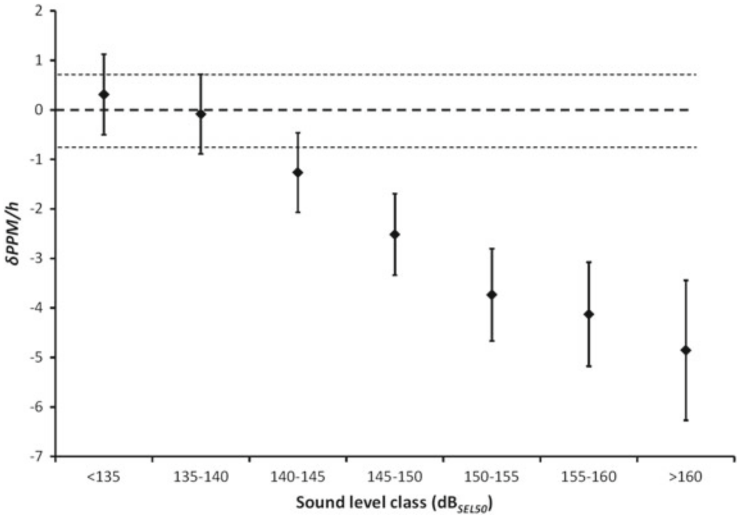

Fig. 92.2 Effect of sound level at 50th percentile of the SEL (5 dB_{SEL50} classes) at rammings on standardized harbor porpoise detection rates (δPPM/h; difference between the temporal scale of hours [PPM/h] and reference parameter of detection rates uninfluenced by pile-driving activity [PPM·s]). Values are means ± SE against average detection rates during a reference period. *Dotted horizontal lines*, mean ± SE of reference parameter

Table 92.2 Values during pile-driving activity at different sound levels (5 dB_{SEL50} classes)

Sound level, dB_{SEL50}	*N*	δPPM/h ± SE	df	*t* value	*P* value	Significance
<135	529	0.30839 ± 0.81168	381	0.37994	0.7042	NS
135–140	511	−0.08752 ± 0.80327	381	−0.10895	0.9133	NS
140–145	471	−1.26633 ± 0.80348	381	−1.57606	0.1158	NS
145–150	404	−2.51656 ± 0.82147	381	−3.06350	0.0023	**
150–155	216	−3.73560 ± 0.93069	381	−4.01381	0.0001	***
155–160	140	−4.12671 ± 1.05013	381	−3.92970	0.0001	***
>160	62	−4.85539 ± 1.41231	381	−3.43790	0.0007	***

δPPM/h standardized harbor porpoise detection rate (difference between the temporal scale of hours [PPM\h] and reference parameter of detection rates uninfluenced by pile-driving activity [PPM·s]), *N* number of data. Significance levels for *P* values: *NS* not significant ($P > 0.05$); **, highly significant ($P \leq 0.01$); ***, most significant ($P \leq 0.001$)

During the operation of BBC 2 under a full air supply, the radius of disturbance was reduced to ~5 km under a given average noise mitigation of 11 dB_{SEL50}. Hence, the application of a BBC 2 reduced the area of equal sound levels by ~90% compared with uninsulated pile-driving activities that, in turn, reduced the area of potential disturbance by pile-driving activities for harbor porpoises by the same proportion.

4 Discussion

During construction of the offshore wind farm Borkum West II, a new noise mitigation system, the BBC, was, for the first time, integrated into the usual construction process of an offshore wind farm without causing any delays. Noise mitigation of the new system resulted in a strong reduction of the spatial and temporal disturbance effects on harbor porpoises. This demonstrated that a positive effect for a species of public interest was achievable by insulation of noise emissions resulting from offshore pile driving.

Operation of the BBC 2 reduced the potential area of disturbance by pile driving for harbor porpoises by 90%. Accordingly, under the assumption of a relatively homogeneous distribution of harbor porpoises on a short-term temporal scale (during operation of a BBC 2) within the restricted spatial range of the study area (tens of kilometers), the average number of disturbed animals would be reduced by 90% as well compared with pile driving without noise mitigation.

Experiences from project HYDROSCHALL-OFF BW II form a substantial base regarding future application of noise mitigation systems as part of offshore wind farm development in Germany. However, findings of other projects indicate that the results of this project may be only partly applicable to other locations; under different conditions, it was not always possible to achieve the noise mitigation rates obtained during this project (e.g., Würsig et al. 2000; Illingworth and Rodkin 2007; Nehls et al. 2007).

Ongoing discussions regarding the assessment of pile-driving noise clearly show that there is great public interest in a description and evaluation of harbor porpoise response to noise pollution (e.g., Brandt et al. 2011; Dähne et al. 2013). The project provided new insights in this respect. However, some questions remained open that should be addressed in future projects. Besides further technical development of bubble curtains, it will be important to investigate their mode of action under different conditions as well as to describe influencing parameters on the sound mitigation of a BBC (Pehlke et al. 2013). As for the harbor porpoise response, it would be desirable to further evaluate the effects of frequency-dependent noise mitigation of a BBC as well as of different durations of ramming periods on the spatiotemporal activity patterns of these animals in future.

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