CHAPTER 2

ON THE EFFECTIVENESS OF UNDERWATER SOUND MITIGATION MEASURES USED DURING PILE DRIVING IN BELGIAN WATERS

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Abstract

During the construction work of the wind park Norther off the Belgian coast, underwater sound mitigation measures have been applied to lower the sound pressure generated during pile driving. The sound mitigation system (insertion loss) applied in this project was a Single Big Bubble Curtain (BBC). In addition, for five monopiles, experiments were conducted using the AdBm Noise Mitigation System, a stationary resonator system, either alone or together with the BBC. In this study, the underwater sound generated was recorded during five full pile driving events, including during three of the stationary resonator experiments. The diameter of the monopiles ranged from 7.2 to 7.8 m. The hammer used during this project was capable of a maximal energy of 3500 kJ. In situ measured zero to peak sound levels (L_{z-p}) showed values ranging from 188 to 200 dB re 1 µPa (normalised to a distance of 750 m from the source) respectively with the higher values when no sound mitigation measures were deployed at all, and with the lower sound levels when the AdBm and BBC noise mitigation systems were both active. Based on our measurements, the sound mitigation achieved by the BBC was in the single digit range, and the only two-digit reduction was achieved when both mitigation systems were working concurrently, achieving an 11 dB re 1 µPa (L_{z-p}) reduction. As previously observed, there was a lower-than-expected performance of the sound mitigation measures, which is likely to be due to local hydrodynamic conditions and or sub-optimal use of the devices.

1. Introduction

The construction of a new wind farm in the Belgian part of the North Sea (BPNS) nowadays relies on the installation of lower numbers of large steel monopiles (7 m diameter and bigger) accommodating generators of more than 7 MW, compared to a larger number of smaller monopiles (5 m diameter) equipped with 3 MW generators as was common practice in the BPNS from 2008 to 2016. Given the size of these monopiles, a large hydraulic hammer is required to drive these steel piles 26 to 47 m into the seafloor. Consequently, an important quantity of energy is introduced underwater in the form of sound that must be damped by noise mitigation systems (insertion loss) to comply with national legislation. In Belgium, impulsive sound should not exceed a zero to peak level of 185 dB re 1 µPa at 750 m distance from the source Belgian State (2018).

In August 2018, Norther NV started the construction of an offshore wind farm at about 13 NM from Zeebrugge. This 370 MW wind farm consists of 44 Vestas V164-8.0 MW wind turbines and one offshore transformer station thus requiring the installation of a total of 45 foundation structures. The diameter of these monopiles ranges from 7.2 to 7.8 m. The pile driving was done using a 3500 kJ hydraulic hammer. Pile driving took place between 6 August and 12 November 2018.

In absence of direct sound mitigation, zero to peak sound levels (L_{z-p}) as high as 204 dB re 1 µPa at 750 m from the source were predicted (Bellmann *et al.* 2017).The concessioner proposed a sound mitigation system consisting of a single big bubble curtain (BBC). In addition, a field test of the experimental AdBm stationary resonator method was to be applied to five monopile installations.

This setup was accepted by the responsible administration and an underwater sound monitoring ensued.

The purpose of this report is first to quantify the emitted underwater sound measured *in situ* at sea and, second, to assess and evaluate the noise abatement achieved by the sound mitigation measures, *i.e.* BBC and AdBm static resonator systems.

2. Material and methods

2.1. Construction activities and local conditions

The first steel monopile of the Norther offshore wind farm was installed on 6 August 2018 (WTG-35-I2) and the last one was piled on 12 November 2018 (WTG-31-K4). A hydraulic hammer MHU 3500S from Menck Gmbh was deployed from the jacking-up platform Aeolus for every piling. With the exception of the Adbm field tests, sound mitigation was always in place during pile driving in the form of a BBC of 660 m long (table 2). The flow of air was provided by seven oil-free compressors (AC PTS 916) at the rate of 43 $m^3 min^{-1}$ each.

For the Adbm field tests, a series of four periods of pile driving were undertaken at constant energy of 1750 kJ for the monopiles WTG 30-J2, WTG 21-F1 and with an energy of 2250 kJ, for WTG 27-K2. Those four phases, that have a duration of 5 to 6 minutes each, are:

- piling reference period with no sound mitigation applied;
- piling period with the AdBm stationary resonator deployed alone;
- piling period with AdBm and BBC applied together;
- piling period with BBC only.

These piling sequences are clearly identifiable in the underwater sound recordings because of the long period of no activity of about 20 minutes separating the different phases of the experiment.

The BPNS is the seat of strong semi-diurnal tides. At the Norther construction site, the tidal current can be in excess of 1.5 m/s at a given time during the moon cycle (Belgian nautical chart D11). In this zone of the North Sea, the semi-diurnal tidal current is changing speed and direction all along the 12h25 tidal cycle.

2.2. Research strategy

Underwater sound generated by driving 7.2 to 7.8 m diameter steel monopiles into the seabed was measured *in situ* during construction. Five full pile driving events were recorded from 12 September 2018 to 18 September 2018 (tables 1 & 3). Two events were measured when only the BBC was operational. The three other events were measured during the field test of the experimental AdBm stationary resonator method.
Various metrics like Level zero to peak (L_{z-p}), Sound Pressure Level (SPL) or the

sound exposure levels of a single stroke 95 percentile (SEL_{95}) were considered. The effectiveness of the sound mitigation measure was assessed comparing the measured value *in situ* on site during the various phases of pile driving with the reference value of the pile driving during the insertion loss experiment.

2.3. Underwater sound measurement equipment

Underwater sound was recorded from two moored stations (fig. 1). Each mooring was equipped with a measuring chain consisting of an acoustic release (Benthos 866 A/P), one underwater sound recorder (RTsys EA-SDA14), one hydrophone (Brüel & Kjær – B&K – 8104 or HTI-96-MIN), and a flotation device used to maintain the systems upright and tied. One additional acoustically commanded pop-up buoy (Benthos 875-PUB) was used for recovery of the mooring block afterwards. The pop-up buoy is attached rigidly to the concrete block to avoid perturbing sound. The sound recorder manufacturer RTsys calibrated the complete measurement chain prior to shipping from the factory. The calibration was verified using a calibrator B&K 4229 (piston-phone) prior to deployment and further verified using a ½ inch precision microphone B&K 4191-l in the laboratory.

Figure 1. Mooring design of the underwater sound measurement equipment. Here on the rear deck of Zeetijger prior deployment.

The moorings were deployed on 28 August 2018 from the work vessel Zeetijger at (WGS84) N 51° 32,503; E 003° 00,967 (mooring 1) and N 51° 31,010; E 3° 00,849 (mooring 2). The distance between the measuring equipment and the piling locations ranged from 439 m to 3758 m. No surface marker was left on site to reduce risks to navigation inside the construction zone as well as to avoid any perturbing sound originating from a line linking a surface buoy to the mooring.

Table 1. Position of the monopiles and instruments in UTM31, distance from the monopile to the measuring equipment (RTsys1 and RTsys2)

Names	Center Point Position (Coordinates)		Distance to RTSys1 (m)	Distance to RTsys2 (m)
	Easting	Northing		
WTG-21-F1	501316.93	5707017.97	3124	439
WTG-27-K2	499778.32	5709684.00	1305	2670
WTG-28-I1	501743.17	5709164.60	1211	2013
WTG-30-J2	501610.29	5710025.85	613	2796
WTG-33-F3	504098.43	5709401.95	3176	3758
RTsys1	501006	5710126		
RTsys2	500982	5707301		

2.4. Underwater sound measurements and post-treatment

Sound pressure was recorded continuously at a sampling rate of 78,125 Hz and stored on hard drives coded on WAV format. One instrument did not work properly and no data could be exploited from mooring 1. Mooring 2 was dedicated more specifically to the AdBm tests and was recording five full piling events (table 1).

MATLAB was used for the post treatment of the records. SEL_{95}, as well as the normalisation of the sound levels to the reference distance of 750m was computed following the Material & Method section of Norro *et al.* (2013).

2.5. Evaluation of noise mitigation measures

For assessing the broadband efficiency of the sound mitigation system or insertion loss, a direct comparison is made here between the measured peak sound levels during the different phases of the AdBm field test. For simplification of the interpretation, the same energy was assumed to be used by the hammer during the insertion loss experiment.

Spectral analysis of the sound pressure levels in 1/3 octave was conducted to examine the efficiency of the insertion loss as a function of the frequency of the generated sound.

2.6. Single big bubble curtain specificities

Mitigation measures introduce an "insertion loss" between the sound source and the surrounding environment.

Table 2. Specificities of the single big bubble curtain, nozzle hose (as provided by the concessioner)

FAD available	> 0,4 m³/m/min
Diameter holes	1,5 mm every 200-300 mm

The best sound reduction is achieved with an optimal air supply and BBC design, *e.g.* distance between holes and dimension of the holes (OSPAR 2014; Nehls *et al.* 2015). When optimised (table 2), BBCs are expected to reduce the sound levels by 14 dB L_{z-p} (range 11-17 dB) or 11 dB SEL (range 9-13 dB; OSPAR 2014). Norro (2018) measured efficiency of a BBC during the Rentel piling work operated in 2017 in the Belgian North Sea. The sound reduction achieved during operations in the field for L_{z-p} was ranging from 11 to 13 dB re 1 µPa. Based on a study from iTap a sound reduction of 19 dB re 1 µPa (L_{z-p}) using the BBC only was predicted prior to construction.

3. Results

In the absence of any noise mitigation, L_{z-p} at 750 m from the source ranged between 198 and 200 dB re 1 µPa. This L_{z-p} was reduced to 189 to 194 dB re 1 µPa when only the BBC was applied. When both noise mitigation systems, AdBm and BBC, were operating concurrently L_{z-p} at 750 m from the source ranged from 188 to 190 dB re 1 µPa (table 3).

SEL_{95} normalised at 750 m ranged for the reference values between 172 and 177 dB re 1 µPa² s while a reduction to a level ranging from 164 to 166 dB re 1 µPa² s was obtained for the combination of AdBm and BBC. For the most frequently used sound mitigation system (BBC only), SEL_{95} ranged from 163 to 174 dB re 1 µPa² s.

The broadband insertion loss (table 3 in bold) of the various mitigation measures applied ranged from 3 to 6 dB re 1 µPa (L_{z-p}) when applying AdBm alone, from 6 to 11 dB re 1 µPa (L_{z-p}) when applying BBC alone and from 10 to 11 dB re 1 µPa (L_{z-p}) when both AdBm and BBC are applied.

The spectral analysis presented at figure 2 shows that the insertion loss

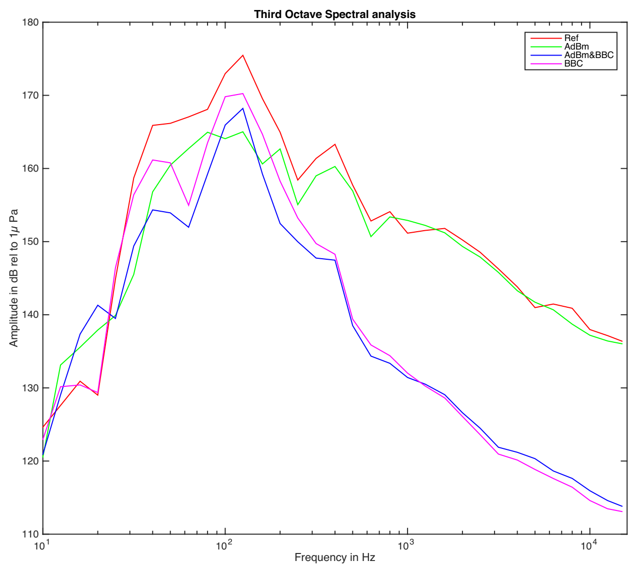

Figure 2. Spectral analysis of the underwater sound pressure level measured during the reference, AdBm, AdBm & BBC and BBC phases of the insertion loss experiment for pile WTG 21-F1 (measured at 439 m distance).

Table 3. Zero to peak sound pressure levels in dB re 1 µPa as measured *in situ* and normalised at 750 m distance from the pile driving location for five piling events measured at the Norther site. Reference is measured during the insertion loss experiment without any direct sound mitigation while Ref-Bellmann is taken as reference for those pile driving events where no period without any mitigation is available. Broadband efficiency estimate of the mitigation measures is based on the difference between measured zero to peak sound pressure level ($L_{z\text{-}p}$) on site during the various phases of the piling during the insertion loss experiments. Normalised at 750 m values are also provided

Northern 2018	**Reference**		**AdBm**			**AdBm & BBC**			**Flow BBC**	**E Hammer**	**BBC**			**Max Observed**		**Distance from source**
Name	$L_{z\text{-}p}$	SEL_{95}	$L_{z\text{-}p}$	SEL_{95}	**Eff AdBm**	$L_{z\text{-}p}$	SEL_{95}	**Eff AdBm & BBC**	$m^3/m/min$	kJ	$L_{z\text{-}p}$	SEL_{95}	**Eff BBC**	$L_{z\text{-}p}$	SEL_{95}	m
WTG-30-J2	189	163	186	159	**3**	179	155	**10**	0,42	1750	182	157	**7**			2796
	198	172	195	168	**3**	188	164	**10**			191	166	**7**			Norm at 750 m
WTG-27-K2	192	166	187	164	**5**	181	159	**11**	0,42	2250	186	161	**6**			2670
	200	174	195	172	**5**	189	167	**11**			194	169	**6**			Norm at 750 m
WTG-21-F1	206	183	200	176	**6**	195	172	**11**	0,42	1750	200	176	**6**			439
	200	177	194	170	**6**	190	166	**10**			194	170	**6**			Norm at 750 m
WTG-28-I1	Ref-Bellmann								0,42	2612				191	168	2013
	204													193	174	Norm at 750 m
WTG-33-F3	204								0,36	2053				178	157	3758
														189	167	Norm at 750 m

efficiency is increasing at higher frequencies than those featuring the maximal transfer of energy into the water column. The latter is located from 100 to 150 Hz. Sound mitigation appears to be more efficient as the frequency of the sound increases above 300 Hz (fig. 2). Both BBC and, BBC and AdBm showed an important decrease in measured sound pressure level above 300 Hz. AdBm showed the best attenuation (about 10 dB re 1 µPa) of the sound pressure level at 63 and 125 Hz while above 300 Hz the attenuation of about 20 dB re 1 µPa is mainly achieved by the BBC.

4. Discussion

During the five complete piling events measured in this study, $L_{z\text{-}p}$ was generally higher than the 185 dB re 1 µPa at 750 m distance from the source which is the MSFD limit in Belgium. The predicted (by the concessioner) reduction of 19 dB re 1µ Pa (broadband) was never obtained during our measurements and this even when both the AdBm static resonator and the BBC were used concurrently. Furthermore, the value obtained for the efficiency of the BBC is below what can be found in literature (Bellmann *et al.* 2017; OSPAR 2014). Several reasons can be at the basis of this lower-than-expected performance of the sound mitigation measures.

The usual cause for lower than expected performance of BBC lies in its sub-optimal set up (Bellmann *et al.* 2017; OSPAR 2014). Airflow as well as hole diameter and spacing on the nozzle hose play an important role in the sound mitigation efficiency (Bellmann *et al.* 2017; OSPAR 2014). Any leakage in the system reduces the effective flow into the nozzle hose. For this project, it is impossible to assess whether such flow could be the reason for the lower performance because exact airflow passing throughout the nozzle hose was not measured during the operation.

Another reason for lower performance may be linked to strong tidal currents (see below). Indeed, the Belgian part of the North Sea is the seat of strong semi-diurnal tidal currents (Nautical chart D11). If one takes into account that the smallest bubbles of air have an ascent speed of 10 to 15 $m.min^{-1}$.

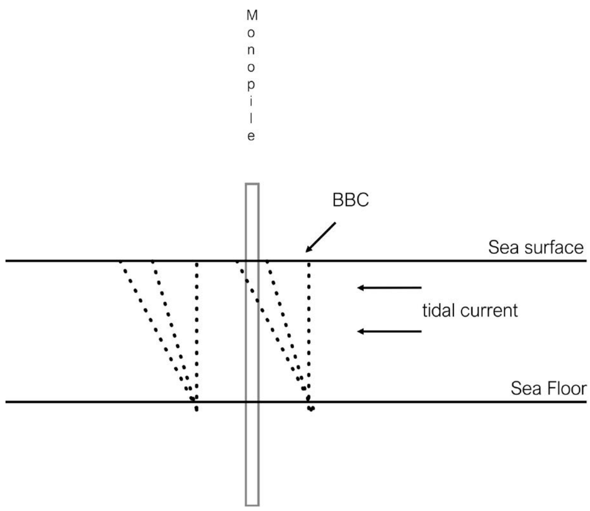

Figure 3. Sketch of the effect of current on the bubble curtain (BBC). Not to scale.

From a depth of about 25 m, 2 minutes are needed to reach the surface and therefore, in presence of a 1 $m.s^{-1}$ current, a drift of about 120 m may be expected.

Since the BBC is deployed featuring a round or sometime elliptical shape diameter of maximum 200 m (cf. nozzle hose of 660 m) it is possible that the bubble curtain will lose part or most of its efficiency and possibly "overtake" the monopile location during piling operations (fig. 3).

A possible optimisation of BBC efficiency in high tidal current situation could be to pile only when the tidal current speed is minimal or at least below a threshold to be determined as a function of depth and nozzle hose diameter.

For two piling events (WTG-28-I1 and WTG-33-F3), the BBC efficiency seems to be higher than for the other measured piling events. This can possibly be explained by the relatively high reference value of 204 dB re 1 µPa that had to be assumed here in absence of direct measurements of the reference value. The reference value was taken from the ITAP model by Bellmann *et al.* (2017). In comparison with the piling events for which we were able to directly measure reference values, we may assume the 204 dB re 1 µPa value to probably be too high by 5 dB re 1 µPa. When applying that difference, the efficiency of the BBC alone is the same as for the other cases presented.

Another point to discuss is the difference in the efficiency of the sound mitigation system in relation to the frequency of the sound. Figure 2 shows that the insertion loss is not equal for every frequency. The efficiency is higher for frequencies above 300 Hz while the higher levels of underwater sound are produced below that frequency and that considering the exposure time to piling works that is limited to 2 h by pile and occurs all in a period of few weeks only for the construction of a wind farm.

In order to comply with Belgian MSFD regulation Belgian State (2018), it is advisable to, at least, test on site the combination of sound mitigation measures before the construction works start and not rely only on predicted efficiency. Another option could also be to reduce the size of the monopiles used or even to come back to using jacket or tripod designs. Using smaller monopiles will reduce the maximum emitted underwater sound to levels that can be efficiently reduced by today's mitigation systems and end up with levels below the Belgian MSFD limits. Another possibility could be to use new methods like blue piling technology or to reconsider using suction bucket foundations.

5. Conclusion

With a level zero to peak ($L_{z\text{-}p}$) in excess of 185 dB re 1 µPa at 750 m (189 to 194) even with both AdBm and BBC sound mitigation measures in place, the emitted sound surpassed the Belgian MSFD limits. Values obtained for the efficiency of noise mitigation systems may be more site specific than previously thought and developers should state under which environmental conditions these reductions in underwater sound were achieved. For future construction activities of large monopiles, it is advisable to test the anticipated sound mitigation system efficiency prior to the start of the work on site in order to be certain to be able to comply with the Belgian MSFD thresholds for impulsive underwater sound.

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