CHAPTER 2

ON THE EFFECTIVENESS OF A SINGLE BIG BUBBLE CURTAIN AS MITIGATION MEASURE FOR OFFSHORE WIND FARM PILING SOUND IN BELGIAN WATERS

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Abstract

The construction works of the Rentel wind farm off the Belgian coast was monitored for the emission of energy into the sea by means of underwater sound (pressure). Thirteen complete piling events were monitored, covering the driving to full depth of 13 steel monopiles of 7,8 m diameter using a hydraulic hammer with a maximum power of 4000 kJ. Sound mitigation in the form of a single big bubble curtain (BBC) was used. Measured zero to peak level (L_{z-p}) normalized to 750 m distance from the source showed values ranging from 185 to 194 dB re 1µ Pa at the end of the piling event when maximal hammer energy is used (2100-4000 kJ). The efficiency of the BBC is in the lower range proposed by the literature with a reduction of a maximum of 11-13 dB re 1 µPa (L_{z-p}). More than one mitigation measure should be used simultaneously in order to comply with the Belgian Marine Strategy Framework Directive requirements for such project.

1. Introduction

The size of commercially available wind turbines has increased in the last decades. Whereas in 1991, the first offshore wind farm used 450 kW turbines currently projects typically use 8 MW or larger turbines. The offshore wind energy sector has had to adapt turbine foundation design in order to keep up with this increase in size. Taking into account the cost and construction time, the followed option has been by increasing the size of the monopile foundations. However, more powerful hammers are required to drive such XL or XXL steel monopiles into the seafloor. As a result, higher levels of impulsive sound are introduced into the marine environment raising concerns about possible negative impacts on marine life (*i.e*, Popper & Hawkins 2012; 2016). In absence of mitigation measures, pile driving of an 8 m diameter monopile would emit impulsive underwater sound zero to peak levels (L_{z-p}) of about 204 dB re 1µ Pa at 750 m distance from the source (ITAP model, see below). The reduction of the generated sound by sound mitigation measures hence no longer is an option but compulsory; this given the need to respect maximum admissible levels of sound defined at national level for the Marine Strategy Framework Directive (MSFD). For Belgium, that limit is set at a maximum L_{z-p} of 185 dB re 1µ Pa at 750 m from the source. In Germany, maximum L_{z-p} must stay below 190 dB re 1 µ Pa at 750 m and sound exposure level (SEL) must be below 160 dB re 1 µ Pa^2 s at 750 m from the sound source.

In 2017, the company Rentel built a new wind farm off the Belgian coast located between the C-Power and the Northwind wind farms. This new wind farm consists of 42 monopiles with a diameter ranging from 7.5 m (10 piles) over 7.8 m (26 monopiles) to 8 m (6 monopiles). For this project, the noise mitigation measure proposed and used was a single big bubble curtain (BBC).

The purpose of this report is (1) to quantify the emitted underwater sound during piling events and (2) to assess and evaluate the efficiency of the noise mitigation measure (insertion loss).

2. Material and methods

2.1. Research strategy

Underwater sound generated by driving an 8 m diameter XXL steel monopile into the seabed while applying a big bubble curtain as sound mitigation measure was measured *in situ* during construction. The L_{z-p}, the sound exposure levels of a single stroke (SEL_{ss}) and the cumulative sound exposure levels (SEL_{cum}) were computed. The effectiveness of the sound mitigation measure was assessed comparing the measured value on site with the theoretical figures obtained for such monopile diameter using the ITAP model.

2.2. Construction activities

The first steel monopile of the Rentel offshore wind farm was installed on 21 July 2017 (RC03) and the last one was piled on 23 September 2017 (RD05). During construction, underwater sound was recorded by means of a moored station during 13 complete pile driving events. A Hydro hammer S-4000 from IHC IQIP (4000 kJ) was deployed from the jacking-up platform Innovation.

Sound mitigation was in place in the form of a single big bubble curtain (BBC) of 700 m long (table 1). The flow of air was provided by eight oil-free compressors (AC PTS 916) of 40.3 $m^3 min^{-1}$ each at a maximum pressure of 10 bar.

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). 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).

2.3. Underwater sound measurement equipment

Underwater sound was recorded from a moored station (figs 1 & 2). The mooring was equipped with a measuring chain consisting of

Table 1. Specificities of the single big bubble curtain, nozzle hose (as provided by the concessioner)

Inner diameter hose	102 mm
FAD (Free Air Delivery)	8x40 m^3/min/compressor 320 m^3/min
FAD per meter	0,44 m^3/m/min
Diameter holes	2 mm every 100-300 mm

an acoustic release (Benthos 866 A/P), one underwater sound recorder (RTsys EA-SDA14), one hydrophone (B&K 8104 or HTG) 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. A wood block (fig. 2) was used to assure a silent behavior of the pop-up buoy in case of strong tidal currents and wave action. The 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 every deployment.

The mooring was deployed on 14 July 2017 from RV Belgica at the position WGS84 N 51° 35,129; E 002° 56,037. The mooring was retrieved on the 25 August 2017 when another one was placed at the position WGS84 51° 35,114 N, 002° 56,04 E. As such, the distance between the measuring equipment and the piling locations ranged from 808 to 4691 m. No surface marker was left on site to reduce navigation risk inside the construction zone as well as to avoid any perturbing sound originating from a line linking a surface buoy to the mooring.

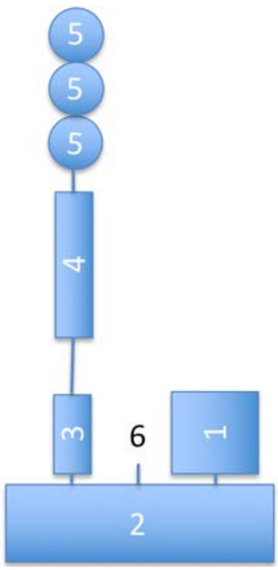

Figure 1. Mooring design of the underwater sound measurement equipment. 1 pop-up buoy (acoustic command), 2 concrete blocks 300 kg, 3 acoustic release, 4 underwater noise recorder & hydrophone, 5 rigid flotation (total 650 N buoyancy), 6 attachment for deployment, total height 3 m, all links in stainless steel cables 8 mm.

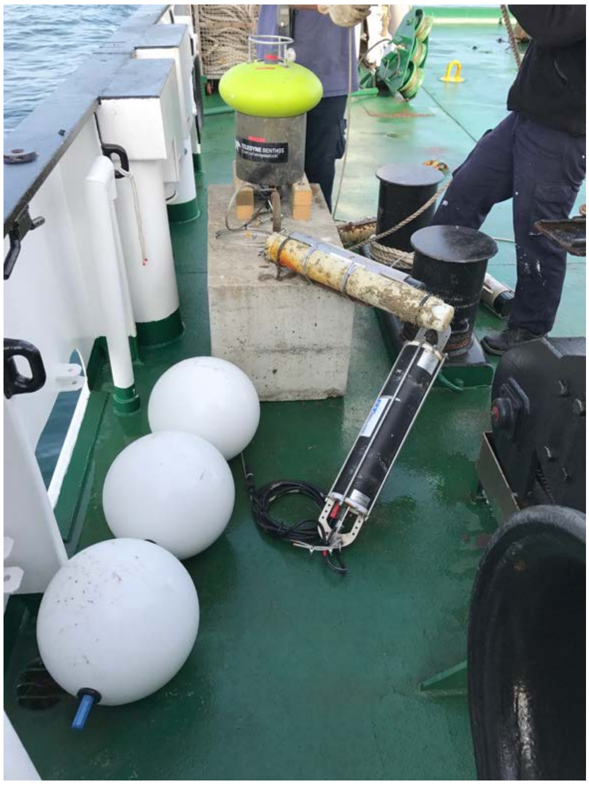

Figure 2. Underwater sound measuring chain prior to deployment from RV Belgica. A C-POD (acoustic porpoise detector) is added to the mooring (next to the acoustic release). A pop-up buoy (far end) is used for recovery of the concrete block. Photograph by A. Norro.

2.4. Underwater sound measurements and post-treatment

Sound pressure was recorded continuously at a sampling rate of 78125 Hz and stored on a hard drive coded on WAV format. During the period of deployment, 13 piling events occurred (table 2).

MATLAB was used for the post treatment of the records. SEL_{ss}, SEL_{cum} as well as the normalization of the sound levels to the reference distance of 750 m were computed following the material and methods section of Norro *et al.* (2013). Because the intensity of the sound depends on the size of the sound

Table 2. Sound data available for the Rentel wind farm piling phase. Position of the monopile and instrument, monopile diameter, distance from the monopile to the measuring equipment (instrument), RTsys1 position for the first measuring chain deployment, RTsys2 position for the second deployment

Location	Center Point Position (Coordinates) as built (WGS84)		Distance to instrument (m)	Monopile diameter (m)
	Latitude	Longitude		
B4	51°34.934' N	2°55.412' E	808	7.8
B5	51°34.670' N	2°55.874' E	872	7.8
B6	51°34.411' N	2°56.346' E	1378	7.8
B7	51°34.164' N	2°56.813' E	1974	7.5
C4	51°34.729' N	2°56.895' E	1237	7.8
C5	51°34.485' N	2°57.305' E	1869	7.8
D2	51°35.915' N	2°56.020' E	1458	7.8
D6	51°34.819' N	2°57.882' E	2196	7.8
E2	51°35.910' N	2°57.089' E	1909	8
E4	51°35.117' N	2°58.518' E	2861	7.5
F3	51°35.857' N	2°58.411' E	3064	7.8
G7	51°35.721' N	2°59.667' E	4337	7.5
G8	51°35.485' N	3°0.058' E	4691	7.5

source and associated hammer, the intensity of the sound increases with the pile diameter.

For assessing the efficiency of the sound mitigation measure, the ITAP model was used to estimate the sound levels generated by the piling without mitigation measures.

ITAP proposes a model based on past observations (Bellmann *et al.* 2017) that allows estimating both SEL and L_{z-p} from the diameter of the monopile to be driven into the seabed.

3. Results

L_{z-p} normalized at 750 m ranged, at the start of the piling when a maximum of 500 kJ was used, from 176 to 187 dB re 1µPa, while at the end of the piling when maximum energy was used, between 186 and 193 dB re 1µPa (table 3).

SEL_{ss} ranged from 165 to 173 dB re 1 µPa^2 s while SEL_{cum} ranged from 200 to 208 dB re 1 µPa^2 s (table 4). The difference between SEL_5 and SEL_{50} (the SEL percentile 5 and 50 respectively) is less than 3 dB. The total energy used for the complete piling event and the total number of strokes are provided as additional information often requested by bio-acousticians (Hawkins & Popper 2016) in order to better evaluate cumulative effects.

Based on the ITAP model (Bellmann *et al.* 2017), piling of a 7.8 m steel monopile produce an average L_{z-p} of 204 dB re 1µPa at 750 m distance (ranging from 199 to 209 dB re 1µPa) and a SEL_{ss} of 179 dB re 1 µPa^2 s (range: 174-184 dB re 1 µPa^2 s). With a reduction of sound of about 11-13 dB re 1 µPa (table 5), the efficiency of the BBC seems to be less than the predicted 14 dB re 1 µPa (ranging 11 to 17 dB re 1µPa) and hence would be closer to the lower limit of sound reduction cited for BBCs (OSPAR 2014). The efficiency of the BBC could probably have been enhanced by an optimal setup of the device (OSPAR 2014). Hole of 1.5 mm diameter (OSPAR 2014) in the hose instead of 2 mm (table 1) may have improved the quality of the mitigation.

Stated flow of 0.44 m^3 m^{-1} min^{-1}seems to be sufficient but one should remember that the bubble curtain is not placed at the surface but below 20 m of sea water. At that depth hydrostatic pressure is three time the

Table 3. Sound zero to peak levels normalized at 750 m distance from the piling location, measured during 13 piling events at the Rentel site. Start is at the start of the piling event within the first 10 minutes; end is for the end of the piling event when the maximum energy was used. Those results include the insertion loss from a single big bubble curtain (BBC)

Location	Distance to instrument (m)	Measured level L_{zp} START (dB re 1µ Pa)	Nomalized level L_{zp} @ 750m START (dB re 1µ Pa)	Measured level L_{zp} END (dB re 1µ Pa)	Nomalized level L_{zp} @ 750m END (dB re 1µ Pa)
B4	808	176	176	192	192
B5	872	182	183	190	191
B6	1378	181	185	189	193
B7	1974	176	182	184	190
C4	1237	180	183	188	191
C5	1869	179	186	185	191
D2	1458	181	185	188	192
D6	2196	180	187	184	191
E2	1909	179	185	185	191
E4	2861	176	184	183	191
F3	3064	175	185	182	186
G7	4337	174	184	175	186
G8	4691	174	184	176	188

Table 4. Computed SEL_{ss} and SEL cumulative SEL_{cum} normalized at 750 m distance from the 13 piling locations as well as total energy provided by the hammer and the number of strokes needed for complete penetration of the monopile. Those results include the insertion loss from a single big bubble curtain (BBC)

Location	SELss @750m (dB re 1 µ Pa^2 s)	SEL CUM (dB re 1 µ Pa^2 s)	Total E (kJ)	Strokes (n)
B5	166	201	6765005	3332
B6	168	203	6046718	3071
B4	170	205	7912667	3547
C4	169	204	4819735	3247
C5	173	208	5064200	3174
E2	167	202	4987828	3035
D6	170	205	5247363	3171
B7	167	202	5573269	2986
E4	169	204	5039575	3072
F3	166	200	4480189	2784
G8	165	199	3948502	2714
G7	166	200	4517827	2562

atmospheric pressure and therefore it a reduced pressure that is present in the SSB when immerged.

In the case presented here, we observe levels that exceed MSFD value as permitted in Germany and the Netherlands (Rumes *et al.* 2016).

Table 5. Efficiency estimate of the single big bubble curtain mitigation measure based on the difference between the theoretically produced zero to peak level of sound (L_{z-p}) at 750 m (ITAP model) of 204 dB re 1µ Pa (on average) and the observed L_{z-p} normalized to 750 m

Location	Nomalized level L_{zp} @ 750m E (dB re 1µ Pa)	Observed efficiency of the BBC (dB re 1µ Pa)	Distance to instrument (m)
B4	192	12	808
B5	191	13	872
B6	193	11	1378
B7	190	14	1974
C4	191	13	1237
C5	191	13	1869
D2	192	12	1458
D6	191	13	2196
E2	191	13	1909
E4	191	13	2861
F3	186	18	3064
G7	186	18	4337
G8	188	16	4691

4. Discussion

During the first few minutes (< 10 min) of the piling, when the energy provided by the hammer is less than 500 kJ and the BBC in place, L_{z-p} is generally below 185 dB re 1µPa which is the MSFD limit in Belgium. In the following stages of a piling event, when the energy provided by the hammer is more than 500 kJ (500-4000 kJ), L_{z-p} is well above the Belgian MSFD limit.

An optimal tuning of the BBC is necessary to obtain the full efficiency of the system and to reach a reduction of about 17 dB re 1µPa for L_{z-p} (OSPAR 2014). The numbers presented in table 5 suggest that the BBC was not optimally configured or that the flow of air inside the BBC was insufficient for optimal noise mitigation (OSPAR 2014). Moreover, even with an optimized BBC, the maximum reduction is 17 dB re 1µPa and remains insufficient to reduce L_{z-p} below 185 dB re 1µPa at 750 m distance (204 - 17 = 187). For such a project more than one mitigation measures must have been used.

Nevertheless, the apparent better efficiency of the BBC observed for F3, G7 and G8 with 18 to 16 dB reduction is due to another effect. It is an under estimation of the L_{z-p} resulting from the computation of the normalized value presented at table 5.

Norro *et al.* 2013 presented in the results section a validated propagation model better suited for the Belgian part of the North Sea and that could have been used for the normalization computation. One should remember that it is generally accepted that for such a comparison of normalized value at 750 m one uses a sound propagation law on '15 log' as introduced and used by Muller & Zerbs (2011). As a result, we surmise that, when the difference between the normalization distance (750 m) and the actual distance between sound source and measurement increases, the underestimation of L_{z-p} increases as well.

Our results demonstrate that, when it is required to install XL or XXL monopiles by pile driving, it will be necessary to use a combination of at least two sound mitigation measures in order to comply with national MSFD regulations, as had been predicted by Rumes *et al.* (2017).

5. Conclusion

With L_{z-p} in excess of 185 dB re 1µPa at 750 m even with BBC sound mitigation measure in place, the BBC proved to be less effective than predicted. For future construction activities involving such XL or XXL monopiles, it will be required to combine two or more sound mitigation measures as to comply with the Belgian MSFD thresholds for impulsive underwater sound.

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