# CHAPTER 2

## AN EVALUATION OF THE NOISE MITIGATION ACHIEVED BY USING DOUBLE BIG BUBBLE CURTAINS IN OFFSHORE PILE DRIVING IN THE SOUTHERN NORTH SEA

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### Abstract

In Belgian waters, in 2019, two wind farm construction projects were ongoing, the Northwester 2 (NW2) and the Seamade (SEA) projects. For both projects, turbine foundations were installed using hydraulic pile driving technique with a double big bubble curtain (DBBC) deployed to minimise the underwater sound levels emitted. For the installation of steel monopiles of 7.4 and 8 m diameter, large hydraulic hammers were used of 3000 and 4000 kJ respectively. These projects were the first to use the DBBC mitigation system in Belgian waters. In this study, the underwater sound generated during 14 full-pile driving events, seven per project, was analysed *in situ*. Measured zero to peak sound levels ($L_{z-p}$) showed values ranging from 183 to 193 dB re 1 µPa when normalised to a distance of 750 m from the source. This represented an estimated sound reduction of 20 dB re 1 µPa for NW2 and 12 to 20 dB re 1 µPa for Seastar. This made NW2 the first offshore wind farm whose pile driving was in compliance with the current Belgian Marine Strategy Framework Directive (MSFD) threshold for impulsive underwater sound.

### 1. Introduction

In Belgian waters, a zone was reserved to develop energy production at sea (fig. 1). By the end of 2020, the last two wind farms of this zone, Northwester 2 (NW2) and Seamade (comprised of the Mermaid & Seastar zones), will have completed construction activities and together with the other six parks, represent nearly 400 operational wind turbines with a combined installed capacity of 2200 MW. Together with the adjacent Dutch Borssele wind energy zone (1500 MW), this area is rapidly becoming the world's largest operational offshore wind energy area.

Steel monopile foundations are by far the most widely adopted substructure foundation system in the shallow Southern North Sea (see chapter 1 in this report).

Construction of NW2 and Seamade required the installation of 24 and 28 large steel monopiles of 7.4 to 8 m diameter, respectively. A large hydraulic hammer was required to drive these steel piles ~50 m into the seafloor. As a consequence, a large quantity of energy was introduced underwater in the form of sound.

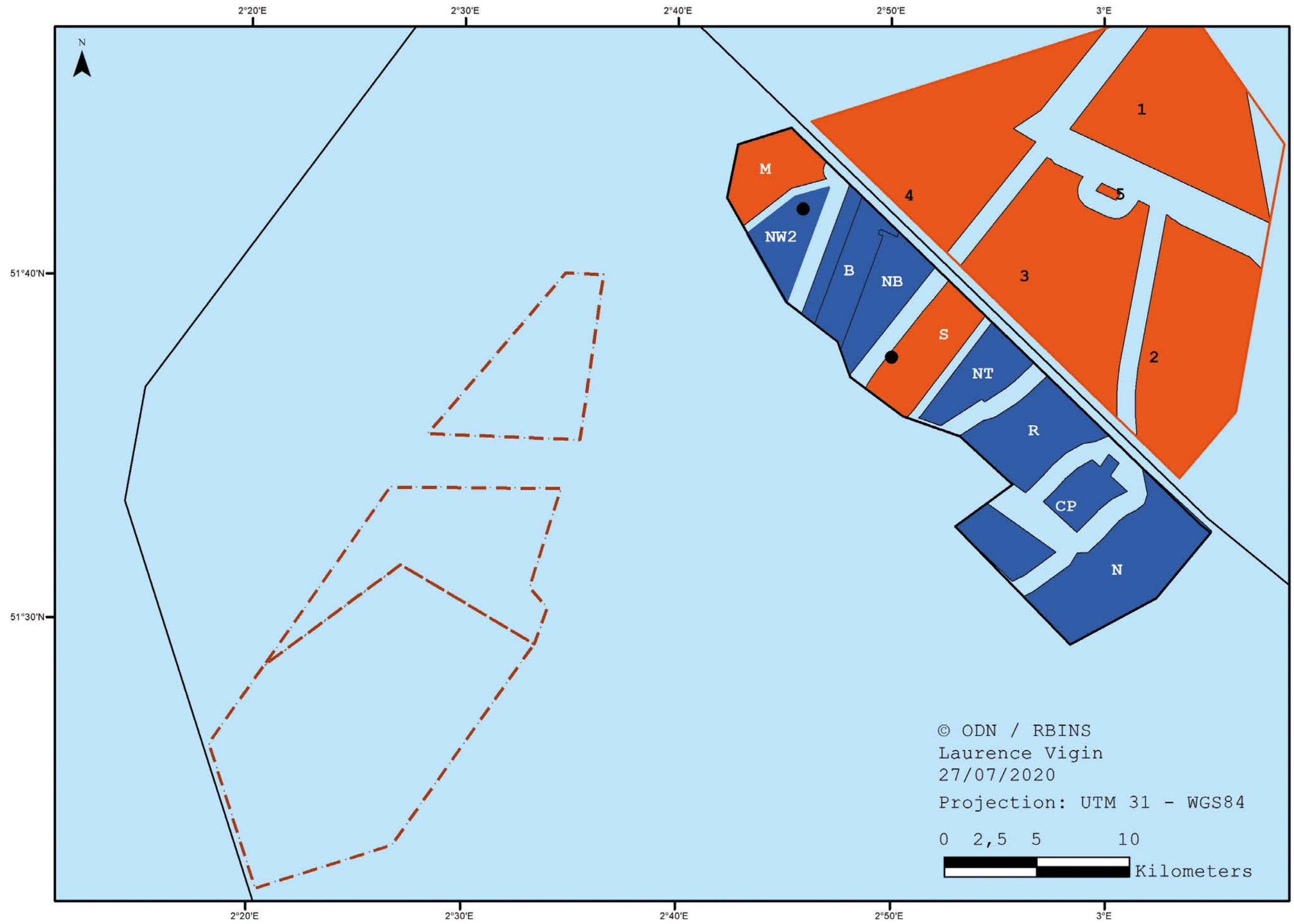


**Figure 1.** Belgian and adjacent Dutch zone of offshore energy production. Belgian zone (North to South). M: Mermaid; MW2: Northwester 2; B: Belwind; NB: Nobelwind; S: Seastar; NT: NorthWind; R: Rentel; CP: C-Power; N: Norther. The hydrophone mooring sites used in this study are represented by the black dot inside S and NW2. Dashed lines: locations of the new Belgian renewable energy zone as delimited in the marine spatial plan 2020-2026.

The piling of such a large steel monopile of 8 m diameter can produce zero to peak sound levels ($L_{z-p}$) of more than 200 dB re 1 µPa at 750 m from the source (Bellmann *et al.* 2017). In Belgium, the impulsive underwater sound should not exceed an $L_{z-p}$ of 185 dB re 1 µPa at 750 m distance from the source (Belgische Staat 2018). The environmental license conditions of NW2 and Seastar requires the developers to comply with this national threshold for impulsive underwater sound.

Both concessioners proposed to use a sound mitigation system consisting of a double big bubble curtain (DBBC). A bubble curtain is formed around a pile by freely rising bubbles created by compressed air injected into the water through a ring of perforated pipes encircling the pile. In a DBBC, two rings of perforated pipes are positioned on the seafloor around the foundation to be piled. Compressors located on the construction vessel feed air into the pipe. The air passes into the water column by regularly arranged holes. Freely rising bubbles form a large curtain around the entire structure, even during tidal conditions, thus shielding the environment from the noise source (OSPAR 2014).

At the end of July 2019, the project NW2 (219 MW installed power) started the construction with the monopile A02 on 29 July and completed the piling work with the installation of the monopile D01 on the

14 November 2019. NW2 is located at about 50 km off the Belgian North Sea coast and is one of the wind farms further away from the coast together with Mermaid.

The Seamade project is comprised of two zones: Mermaid (252 MW installed power) and Seastar (235.2 MW installed power). Seamade construction started on 8 September at Mermaid and on 21 September for Seastar with monopile SE1 at some 40 km from shore. The Seastar zone is located between Nobelwind and Northwind. The Seamade piling work was concluded on 2 January 2020 with the last Seastar monopile SF2.

The purpose of this report is to quantify the emitted underwater sound measured *in situ* at sea and to discuss whether the use of the double big bubble curtain (DBBC) noise mitigation system, as selected by both projects, is appropriate to comply with Belgian legislation on emitted impulsive underwater noise.

## 2. Material and methods

### 2.1. Construction activities and local conditions

The large steel monopiles at NW2 were drilled in the seafloor using a hydraulic hammer IHC Hydrohammer S-3000 capable of producing a maximum percussive energy of 3000 kJ while the installation at Seastar used an IHC Hydrohammer S-4000 capable of a maximum of 4000 kJ. NW2 deployed the hydraulic hammer from the jacking-up platform 'Vole au vent' while the DBBC was operated by the support vessel Thor Express using 21 compressors of a total Free Air Delivery (FAD) of 0,45 $m^3$ $min^{-1}$ $m^{-1}$. The nozzle-hoses' length was 720 m for the inner BBC and 900 m for the second BBC layer. At Seastar the IHC S-4000 was operated from the jack-up platform 'Innovation' for every piling while the DBBC was operated by the support vessel Master express equipped with 24 SCANTECH ST 1600 HAT RS compressors capable of a FAD of 40,5 $m^3$ $min^{-1}$ each into a double bubble curtain HY100. The nozzle-hoses' length was 750 m (inner hose) and 990 m (second layer).

The BPNS is the seat of strong semi-diurnal tides. At both construction sites, the tidal current can be more than 1.5 m/s at a given time during the moon/tidal cycle (Belgian Nautical chart D11). In this North Sea zone, the semi-diurnal tidal current is changing speed and direction all along the 12 h 25 tidal cycle.

### 2.2. Research strategy

The underwater sound generated by driving of 7.4 and 8 m diameter steel monopiles into the seabed was measured *in situ* during construction. Fourteen full pile driving events were recorded from 29 July 2019 to 21 December 2019 (tables 1 & 3). Various metrics, including $L_{z-p}$, sound pressure level (SPL), and the sound exposure levels of a single stroke 95 percentile ($SEL_{95}$) were considered.

### 2.3. Underwater sound measurement equipment

The underwater sound was recorded from two moored stations (fig. 2). 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 to recover the mooring block after deployment. The pop-up buoy was attached rigidly to the concrete block to avoid perturbing sound. The sound recorder manufacturer RTsys calibrated the complete measurement chain before shipping from the factory. The calibration was verified before and after deployment in the laboratory. This calibration was made using a calibrator


**Figure 2.** Illustration of the mooring design of the underwater sound measurement equipment (here Norther deployment).

**Table 1.** Position of the monopiles and instruments in UTM31, distance from the monopile to the measuring equipment NW2 for Northwester 2, and SEA for Seastar mooring.

| Names | Center Point Position (Coordinates) | | Distance to NW2 | Distance to SEA |
|---|---|---|---|---|
| | UTM 31 | | | |
| | Easting | Northing | in m | in m |
| A02 | 484308 | 5727043 | 912 | |
| A03 | 484641 | 5728036 | 947 | |
| B01 | 483747 | 5727286 | 468 | |
| D02 | 482093 | 5725927 | 2458 | |
| D04 | 480887 | 5726411 | 3151 | |
| F02 | 483509 | 5724926 | 2837 | |
| F03 | 483242 | 5724201 | 3587 | |
| NW2 instrument | 483737 | 5727754 | | |
| SEA instrument | 488500 | 5719748 | | |
| SS-OSS | 489230 | 5719261 | | 877 |
| SA02 | 489882 | 5718628 | | 1779 |
| SA03 | 490550 | 5718361 | | 2475 |
| SF01 | 490488 | 5719306 | | 2037 |
| SB03 | 487278 | 5718257 | | 1927 |
| SA04 | 489842 | 5717880 | | 2300 |
| SA05 | 489013 | 5717467 | | 2337 |

**Table 2.** Specificities of the double big bubble curtain, nozzle hose (as provided by concessioners Northwester 2 – NW2 and Seamade – SEA).

| | |
|---|---|
| FAD available NW2 | 0.45 $m^3\ m^{-1}\ min^{-1}$ |
| Diameter holes NW2 | 1.5 mm every 200 mm |
| Length inner & outer NW2 | 720 m & 900 m |
| Distance from monopile & DBBC | 55 m & 40 m |

| | |
|---|---|
| FAD available SEA | > 0.5 $m^3\ m^{-1}\ min^{-1}$ |
| Diameter holes SEA | 2 mm every 200 mm to 300 mm |
| Length inner & outer SEA | 750 m & 990 m |
| Distance from monopile & DBBC | 100 m & 40 m |

B&K 4229 (piston-phone) equipped with a ½ inch precision microphone B&K 4191-l.

The mooring for NW2 was deployed on 26 July 2019 from the research Vessel Simon Stevin at position (WGS84) N 51° 42,03; E 002° 45,88 (fig.1) and for Seastar by the BNS Belgica on 6 November 2019 at the position (WGS84) N 51° 37,72; E 2° 50,03 (fig.1). The distance between the measuring equipment and the piling locations ranged from 468 m to 3587 m. No surface marker was left on-site to reduce risks to navigation inside the construction zone and avoid any perturbing sound originating from a line linking a surface buoy to the mooring.

### 2.4. Underwater sound measurements and post-treatment

Sound pressure was recorded continuously at a sampling rate of 78125 Hz and stored on hard drives as WAV files.

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 750 m, were computed following Norro *et al.* (2013).

### 2.5. Double big bubble curtain (DBBC) specificities

Mitigation measures introduce an 'insertion loss' between the sound source and the surrounding environment. Both projects used a double big bubble curtain to reduce the emitted underwater sound produced by pile driving. However, the detailed technical specificities are different for each project, and they are summarised in table 2.

## 3. Results

During the pile driving at NW2, $L_{z\text{-}p}$ at 750 m from the source ranged between 183 to 185 dB re 1 µPa (table 3).

While during the piling of Seastar the level zero to peak ranged from 183 to 193 dB re 1 µPa.

The insertion loss efficiency was increasing at higher frequencies while one may remember that pile driving is producing its highest energy at low frequencies (below 300 Hz; fig. 3).

## 4. Discussion

### 4.1. Noise reduction achieved

During the hydraulic pile driving operations at Northwester 2, the *in situ* measured $L_{z\text{-}p}$ values remained below the threshold imposed by the Marine Strategy Framework Directive (MSFD) in Belgian waters. This was almost the case for the piling operated at Seamade even if on some occasions the limit of 185 dB re 1 µPa at 750 m from the source was exceeded (table 3).

In general, a level reduction of about 25 dB (peak level $L_{z\text{-}p}$) is assumed for a DBBC (OSPAR 2014; Bellmann *et al.* 2017). As no pile driving events have been realised without mitigation for these projects, it is difficult to accurately assess the achieved

**Table 3**. Name, distance from the recorder, date of operation, pile diameter, zero to peak sound levels in dB re 1 µPa as measured *in situ*, $SEL_{95}$ computed, maximal energy deployed by the hammer and $L_{z\text{-}p}$ normalised at 750 m distance from the pile driving location for seven piling events measured at the Northwester 2 (NW2) and Seastar (SEA).

| Names | dist. | dist. | Date of piling | Pile diameter | $L_{ZP}$ measured | $SEL_{95}$ measured | Max. energy | $L_{ZP}$ at 750 m |
|---|---|---|---|---|---|---|---|---|
| | m | m | | M | dB re 1 µPa | dB re 1µPa² S | kJ | |
| NW2 | Hammer S-3000 & Mitigation = DBBC | | | | | | | |
| A02 | 912 | | 29/07/2019 | 7.4 | 181 | 156 | 1600 | 183 |
| A03 | 947 | | 15/08/2019 | 7.4 | 180 | 159 | 1480 | 183 |
| B01 | 468 | | 04/08/2019 | 7.8 | 188 | 162 | 1500 | 183 |
| D02 | 2458 | | 12/08/2019 | 7.6 | 174 | 157 | 1600 | 185 |
| D04 | 3151 | | 27/08/2019 | 7.4 | 172 | 154 | 2100 | 185 |
| F02 | 2837 | | 07/08/2019 | 7.8 | 173 | 154 | 2200 | 185 |
| F03 | 3587 | | 25/08/2019 | 7.8 | 173 | 152 | 2200 | 185 |
| SEA | Hammer S-4000 & Mitigation = DBBC | | | | | | | |
| SS-OSS | | 877 | 20/11/2019 | 8 | 192 | 170 | 3500 | 193 |
| SA02 | | 1779 | 07/12/2019 | 8 | 182 | 163 | 2600 | 188 |
| SA03 | | 2475 | 05/12/2019 | 8 | 177 | 155 | 1600 | 185 |
| SF01 | | 2037 | 11/12/2019 | 8 | 178 | 158 | 2500 | 185 |
| SB03 | | 1927 | 21/12/2019 | 8 | 181 | 155 | 1700 | 187 |
| SA04 | | 2300 | 04/12/2019 | 8 | 176 | 156 | 2300 | 183 |
| SA05 | | 2337 | 03/12/2019 | 8 | 179 | 158 | 2000 | 186 |

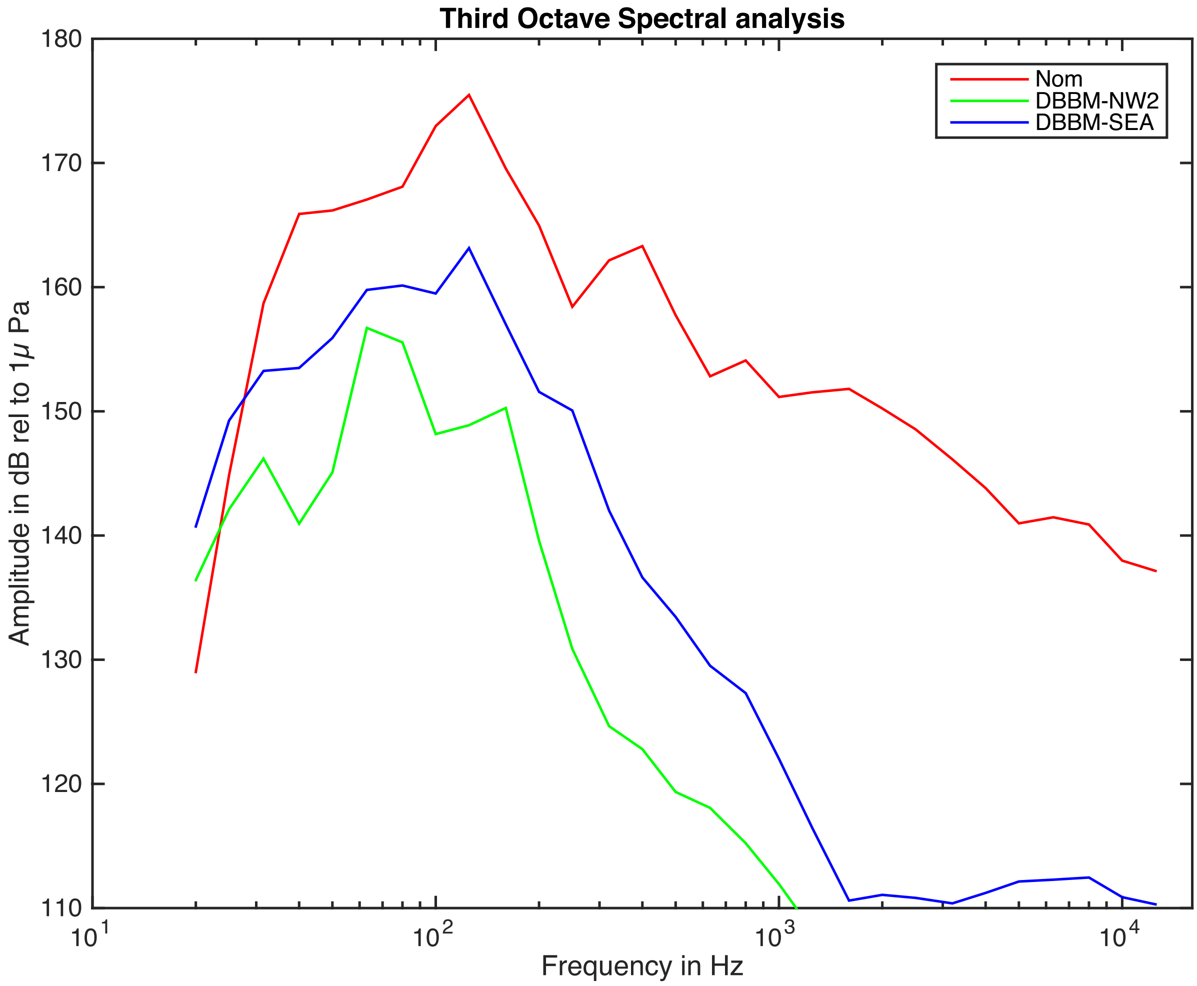


**Figure 3.** Spectral analysis of the underwater sound pressure level measured *in situ* during piling operated without mitigation measures (Norro 2018) and using the double big bubble curtain at Northwester 2 and Seastar. Respectively Nom, DBBM-NW2, and DBBM-SEA.

reduction of the DBBC in these cases. For a rough assessment, theoretical values given by Bellmann *et al.* 2017 can be used. For an 8 m diameter steel monopile zero to peak level of 205 dB re 1 µPa is expected when no mitigation is used. Using that figure for the piling operated at NW2, an efficient 20 dB re 1 µPa is observed while it is lower for Seastar with a range of 12 to 20 dB as observed in table 3. Norro (2019) showed the possible influence of high tidal current featuring the Belgian continental plate on bubble curtains' efficiency, which may explain this difference (see below).

### 4.2. Technical aspects affecting noise mitigation

Both projects used different hydraulic hammers, with 3000 kJ for NW2 and 4000 kJ for Seastar but similar mitigation measures with DBBC. However, the setup of the DBBC was different for the two projects (table 2).

Another consideration is the optimisation of the DBBC. One important aspect is the size and distance between the successive holes on the nozzle hose (table 2). Based on Bellmann (2017), the optimal sound reduction is achieved for a hole of 1 to 2 mm diameter and spaced by 20 to 60 cm. Both projects presented here fit the 'optimal' requirements. The same applies to the Free Air Delivery (FAD) even if that parameter is more difficult to assess in the field. It is based on a theoretical value computed from the number and the given specification of the used compressor. On some occasions, the complete number of compressors could not be used. On one occasion during our survey of Seastar and for the installation of SB03, 22 compressors out the 23 foreseen were used.

One may remark that in case of damage to the nozzle hoses, some leakage may appear that will reduce the system's efficiency. No such damage was reported.

Table 3 showed that both projects' maximum energy were different with a higher value for Seastar. It is generally accepted that an increase of 500 kJ for the hammer energy corresponds to an increase of 2-3 dB re 1 µPa in $L_{z\text{-}p}$ measured at 750 m distance from the source (Müller *et al.* 2019).

### 4.3. Operational aspects affecting noise mitigation

The tidal current may affect the efficiency of bubble curtains. When the current is high, the bubble curtain may be shifted by the current and may be displaced beyond the monopile's footprint, reducing the mitigation effect. NW2 considered a maximum tidal current of about 1.2 m/s, while Seastar considered a mean current of 0.6 m/s. It is the local instantaneous tidal current that affects the bubble curtain. Suppose the mean current is used for the setup of the DBBC. In that case, it is advisable to concentrate the piling operation on the tidal windows characterised by tidal current speeds lower or equal to the mean current speed value. The shape of the DBBC is better designed, taking into account the maximum tidal current's local direction and speed.

Another point to discuss is the difference in the sound mitigation system's efficiency with the frequency of the sound. Figure 3 confirms that the efficiency of the mitigation measure is not equal at every frequency. The efficiency is higher for frequencies above 300 Hz while the energy emitted underwater is mainly below that frequency during piling operated installation.

To comply with Belgian MSFD regulation Belgische Staat (2018) it is advisable to, at least, test on-site the combination of sound mitigation measures as they will be deployed and used before the construction work starts and not to rely only on theoretically predicted efficiency. From the experiment conducted during the Norther wind farm construction in 2017 (Norro 2018), it was shown (Bellmann personal communication) that sound reduction figures obtained from the German waters cannot be transferred as such in Belgian water. This is at least due to the difference in tidal current between the North Sea regions.

## 5. Conclusion

Compared to previous projects (Norro 2018, 2019), the use of DBBC enhanced compliance with the national MSFD limit with $L_{z\text{-}p}$ ranging from 183 to 193 dB re 1 µPa at 750 m from the source. The sound emitted during pile driving for the Seamade project regularly exceeded the Belgian MSFD threshold for impulsive sound of 185 dB re 1 µPa at 750 m despite using a DBBC noise mitigation system. However, using a similar DBBC, the Northwester 2 project managed to comply with regulations. Little differences between both project setups existed except for the hydraulic hammer used that was more powerful for the Seamade project with a 4000 kJ hydraulic hammer deployed to install a little larger monopile. Further improvements on noise reduction could be obtained by an obligatory fine-tuning of noise mitigation measures at the start of new projects *e.g.* the influence of tidal currents must be taken into account with pile driving restrictions the windows of maximal tidal current if necessary.

## References

Bellmann, M.A., Schuckenbrock, J., Gündert, S., Müller, M. & Remmers, P. 2017. Is there a state-of-the-art to reduce pile-driving noise? In J. Köppel (ed.), *Presentations from the CWW2015 Conferences*. Berlin: Springer.

Belgian State. 2018. Actualisatie van de initiële beoordeling voor de Belgische mariene wateren. Kaderrichtlijn Mariene Strategie – Art. 8 lid 1a & 1b. Brussel: BMM, Federale Overheidsdienst Volksgezondheid, Veiligheid van de Voedselketen en Leefmilieu, 243 p.

Müller, A., Ainslie, M., Leaper, R., Merchant, N. & Norro, A. 2019. Revision of the TG noise monitoring guidance. Sound exposure levels of pile driving noise with/without noise protection measures. Background paper, Report No. M 146361/06, Müller-BBM Hamburg, 35 p.

Norro, A., Rumes, B. & Degraer, S. 2013. Differentiating between underwater construction noise of monopile and jacket foundations for offshore windmills: a case study from the Belgian part of the North Sea. *The Scientific World Journal.* https://doi.org/10.1155/2013/897624

Norro, A. 2018. On the effectiveness of a single big bubble curtain as mitigation measure for offshore wind farm piling sound in Belgian waters. In S. Degraer, R. Brabant, B. Rumes & L. Vigin (eds), *Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Assessing and Managing Effect Spheres of Influence*. Series 'Memoirs on the Marine Environment'. Brussels: Royal Belgian Institute of Natural Sciences, OD Natural Environment, Marine Ecology and Management Section, pp. 19-25.

Norro, A. 2019. On the effectiveness of underwater sound mitigation measures used during pile driving in Belgian waters. In S. Degraer et al. (eds), *Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Marking a Decade of Monitoring, Research and Innovation*. Series 'Memoirs on the Marine Environment'. Brussels: Royal Belgian Institute of Natural Sciences, OD Natural Environment, Marine Ecology and Management Section, pp. 19-24.

OSPAR. 2014. OSPAR inventory of measures to mitigate the emission and environmental impact of underwater noise. OSPAR Commission Biodiversity Series, 34 p.