CHAPTER 6

Qualifying and quantifying offshore wind farm-generated noise

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The construction, operation and dismantling of offshore wind farms generate noise both above and under water that may be of environmental concern. The maximum detected sound power level of the above water pin piling noise for example, reached 145 dB(A), while the operational sound power level amounted to 105-115 dB(A) at high wind speed. Underwater construction noise was close to ambient noise levels for gravity based foundations (about 115 dB re 1 µPa RMS), while pin piling and especially monopile piling produced excessive levels of underwater noise up to 194 dB re 1 µPa (zero to peak level at 750m), attenuating to ambient noise levels at a distance of up to 70 km. Whether or not such noise levels are to be considered acceptable will depend on the future implementation of proposed regulations into the Belgian legislation.

INTRODUCTION

In the past decade, the potential impact of underwater noise pollution has been increasingly recognised at the international level, with several intergovernmental bodies, including the UN General Assembly and the UN Convention on Migratory Species, calling for multilateral efforts to minimize the risk of adverse effects on the marine environment. (European Parliament, 2004) (Marine Mammal Commission, 2007) (International Fund for Animal Welfare, 2008), (International Maritime Organisation, 2009), At the European level, the new EU Marine Strategy Framework Directive has identified noise as one of the pressures that need to be controlled to achieve the 'good environmental status' of European marine waters (Anonymous, 2012a). The Belgian part of the North Sea (BPNS) hosts numerous human activities generating noise, including sand and gravel extraction, the installation of pipelines and cables, military exercises as well as intense shipping. As a recent activity, offshore wind farm construction and operation now contribute to the human-induced noise in the BPNS.

Four different phases, each with specific noise emitted, should be distinguished during a wind farm life cycle (Nedwell and Howell, 2004): (1) the reference situation before the start of the construction, (2) the construction phase, (3) the operational phase and (4) the dismantlement phase. Noise emissions associated with the construction phase include e.g. increased shipping traffic, dredging activities, cable trenching, the installation of the scour protection and pile driving. During the operational phase of a wind farm, various kinds of lower level, yet chronic (at least 20 years), noise is expected to propagate above and under water, among which machine noise, self noise generated by the blades passing through the air, noise due to inflow turbulence and noise generated by vibration of the turbine propagating into the water through the foundation. No information is available about the noise during the wind farm dismantling phase as this activity has yet to take place.

This chapter focuses on the qualification and the quantification of wind farm generated noise both above and under water during the construction and operational phase.

MONITORING STRATEGY

Above water noise

The above water or airborne noise level generated by the hammer during a pin pile piling event (jacket) was measured at a short distance (at about 284 m). The source power levels obtained from measurements during piling were used to estimate the impact distance of construction activities in the vicinity for different meteorological conditions using the parabolic equation numerical technique (Dekoninck and Van Renterghem, 2012).

Source power measurements of the operational phase of an offshore turbine are problematic due to the instrument unfriendly conditions. Two approaches were tested. At the one hand, measurements were made from a RHIB at various distances of the wind farm and at the other hand, continuous noise monitoring was set up on the platform of an operational turbine. Measurement conditions in a RHIB are highly limited due to safety issues for the persons on board (wave height) and due to the disturbing noise of waves breaking against the RHIB. Wind turbines at high production and hence high noise emission conditions cannot be monitored with this technique, but a good reference for the offshore background noise levels could be established. One of the remarkable findings was the presence of low frequency background noise related to engines of large ships at long distance. Long term measurements at the wind turbine platform of a 5 MW turbine of C-Power (at approximately 15 m above the water surface and at a minimum 30 m distance from the blade tip) proved to be a useful technique to evaluate the noise emission of a wind turbine in operational conditions.

Underwater noise

Before the construction the background or ambient noise, with both a natural and a human induced component (eg. shipping, rain, waves…), was measured at the Thorntonbank and the Bligh Bank respectively by Henriet et al. (2006) and by Haelters et al. (2009). Construction and operational noise were measured at both the Thorntonbank and the Bligh Bank. Real time noise recordings of maximum 20 minutes each were performed from a RHIB drifting in silent mode with a Brüel & Kjær hydrophone (type 8104) deployed at 10 m depth. A Brüel & Kjær amplifier (Nexus type 2692-0S4) allowed for an amplification of the signal, prior to its recording with an MARANTZ Solid State Recorder (type PMD671), operated at the highest possible sampling rate of 44.100 Hz. All signals recorded were post-treated for detecting maximum peak levels (zero to peak L_{z-p}), used to characterise impulsive noise events (Betke, 2008). Raw measurements were normalised to a distance of 750 m, taken as a standard distance for e.g. German and Belgian underwater noise measurements (Müller and Zerbs, 2011; Anonymous, 2012; see Ainslie et al., 2010). The third octave spectrum was used to identify the spectral window of the noise. Other parameters are also computed and more information on the standardized protocol could be found in Norro et al. (2013). We finally used the collected information on L_{z-p} to estimate offshore wind farm-generated noise propagation in the shallow water environment of the BPNS. A simple propagation model (regression) was fit through the data collected at different distances, which together with the addition of an attenuation term allowed for underwater noise propagation modelling (for details: see Norro et al. 2013).

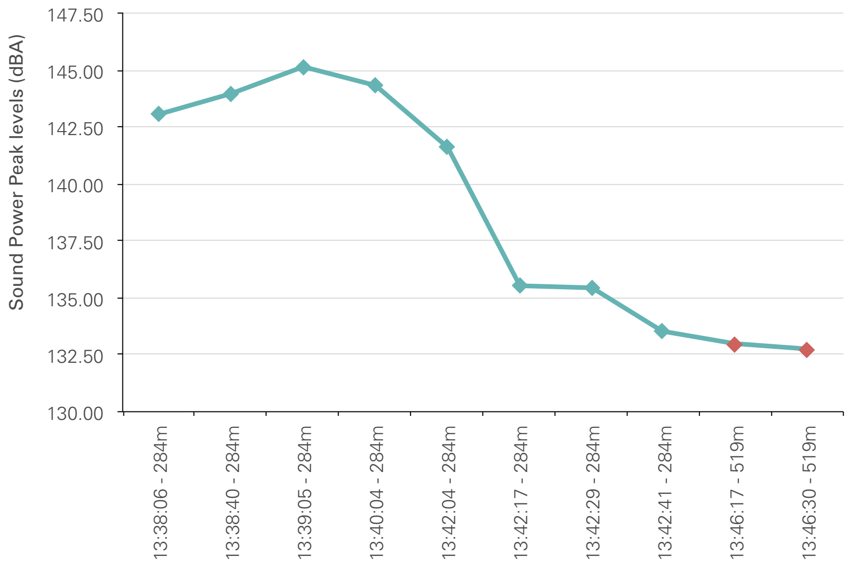
The three foundation types used in the Belgian waters.

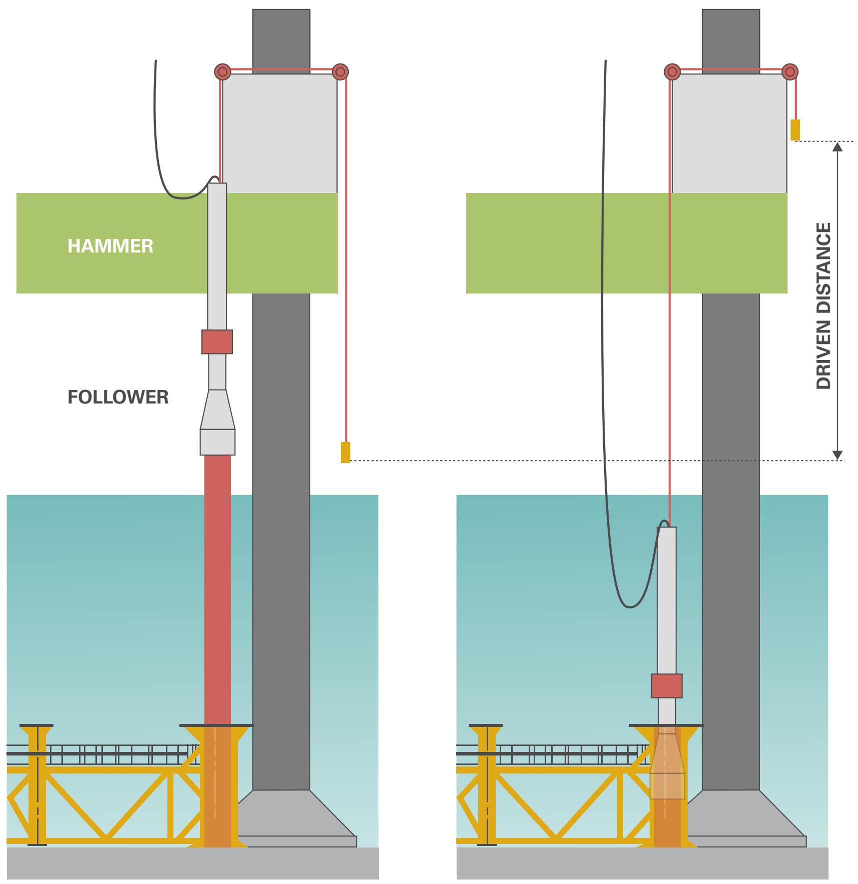
WIND FARM-GENERATED NOISE FEATURES

Above water noise characteristics

The maximum detected source power level of the above water noise during piling was 145 dB(A), but the source power level was highly dependent on the progress of the piling (Figure 1). Firstly, an increase is detected while the piling power is gradually reaching its maximum. While the pile is driven into the seabed, the noise emission drops when the largest section of the pile is below the water surface. Piling activities could be detected in low background noise conditions at a distance of up to 10 km from the source and hence cannot be heard from the coast.

Figure 1. Sound power of the peak levels of piling activity change during the piling progress. Blue points are based on measurements at 280 m distance from the pile, red points at 520 m.





Self noise generated by the blades passing through the air, was detected to be the most important source of sound during operation in modern horizontal axis wind turbines. It occurs when boundary layer turbulence passes the trailing edge of the blade and increases when the boundary layer separates or vortex shedding occurs. Atmospheric conditions could affect the generated sound power in different ways. Boundary layer wind gradients may result in non-optimal inflow conditions for some of the blade positions and inflow turbulence may differ depending on the weather. It can be expected that offshore conditions are more stable than onshore conditions. Noise measurements were evaluated against wind speed at hub height and production data (Figure 2). For very low wind speeds and correspondingly low production, noise levels increase with wind speed but as soon as production is above 2 MW or wind speed is over 9 m/s at hub height, a plateau is reached. Only when production reaches 4.5 MW, which roughly corresponds to wind speeds of 12 m/s at hub height, the noise level starts to rapidly increase again. This could be explained by the changing blade pitch that is used to limit the rotation speed at very high wind speeds, but it could also be caused by the interaction of the wind with the microphone or by secondary sources such as breaking waves. The overall A-weighted sound power level calculated backward from these measurements amount to 102-105 dB(A) for wind speeds between 8 and 12 m/s at hub height and to 105-115 dB(A) for wind speeds higher than 12 m/s. Meteorological effects on sound propagation are limited to a few hundred meters – typically of relevance for onshore operations – because of the height of the source. Long distance propagation over several kilometres over the sea surface depends on meteorological conditions. Spectral data showed a faint tonal peak at low frequencies that increases with production (and rotation speed), which is expected to have a mechanical origin. This indicates that the mechanical noise generated by e.g. the gearbox and the generator may be less carefully encapsulated for these offshore wind turbines compared to onshore wind turbines, in which a significant effort is put into noise reduction. The main contribution is however broad band noise centred between 300 and 800 Hz for the most significant operational range. This spectrum corresponds to what can be expected for such large wind turbines (Møller et al., 2011).

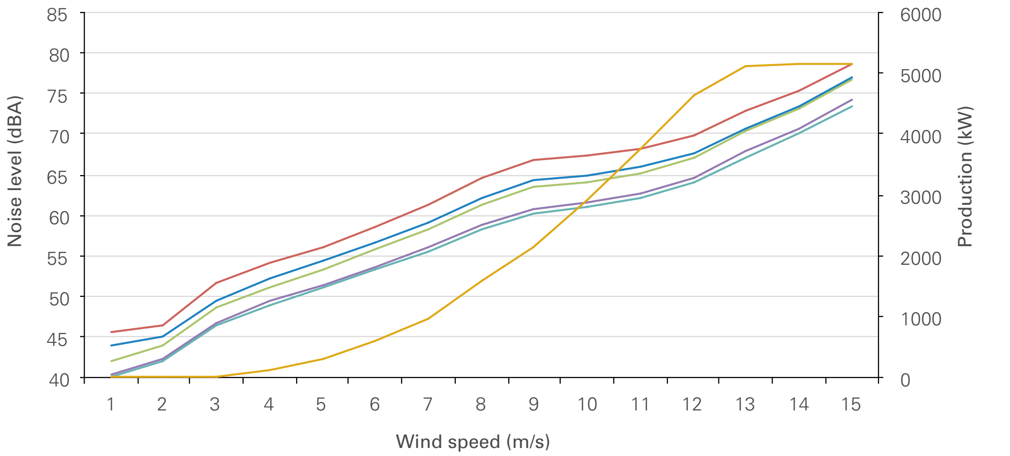


Figure 2. Noise level on the wind turbine platform as a function of wind speed and production.

Underwater noise characteristics

The ambient underwater noise amplitude ranged from 95 to 110 dB re 1 µPa in the 20 Hz to 3 kHz frequency window. The amplitude decreased to 80 dB re 1 µPa at 10 kHz. Slightly higher values were found at the Thorntonbank site (see Henriet et al., 2006), where also a peak at 100 Hz was detected. Both the increase in amplitude and the extra peak may be attributed to the location of the interconnector pipeline and/or the shipping route that are closer to the Thorntonbank than to the Bligh Bank.

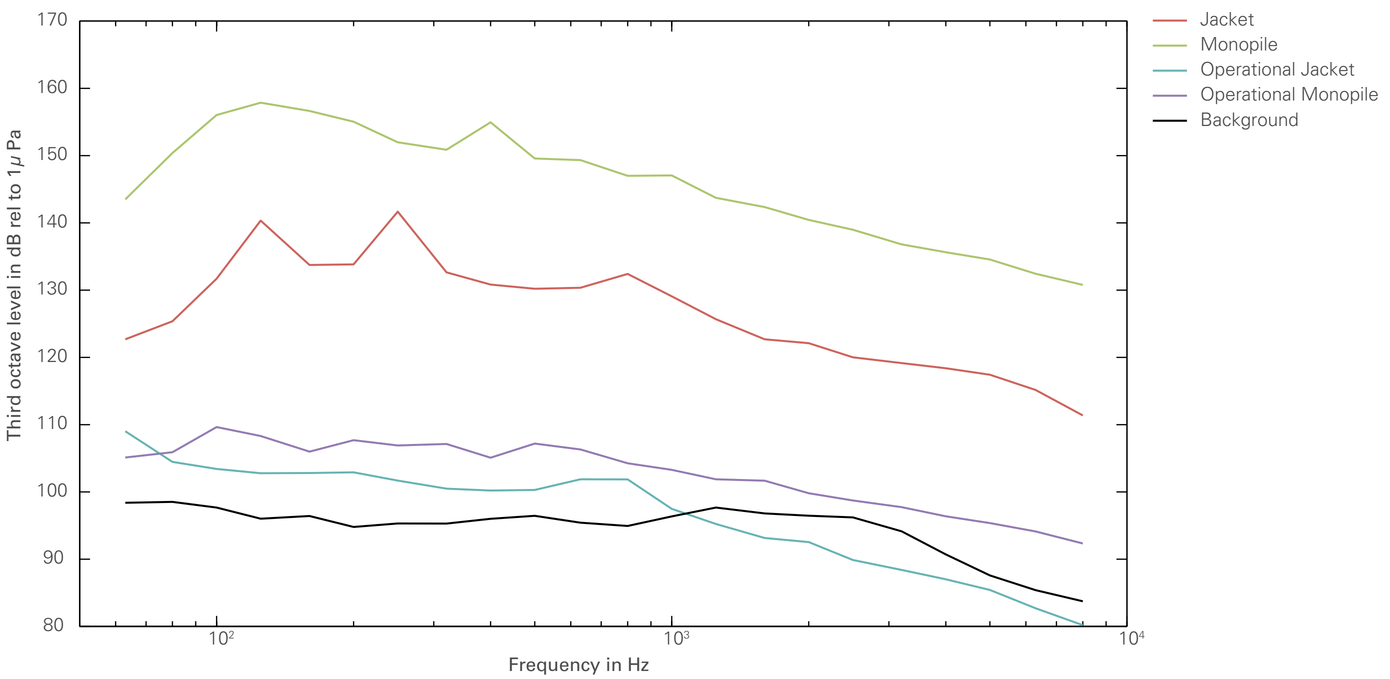
Jacket pin pile (left) and monopile (right) driving preparation at the Thorntonbank and Bligh Bank.

As the installation of gravity based foundations (GBF) do not require piling, the construction of GBF wind turbines may be considered relatively silent as most of the noise is derived from an increase of shipping and dredging operations with RMS noise levels of about 115 dB re 1 µPa, i.e. little higher than the ambient noise level (Haelters et al., 2009). Piling events however are known to produce much higher peaks in noise levels. The piling of 5 m diameter monopiles at the Bligh Bank for example produced an $L_{z\text{-}p}$ of 179 to 194 dB re 1 µPa as measured and normalized at a distance of 750 m from the piling location, while piling 1.8 m diameter pin piles for the jacket foundations at the Thorntonbank showed $L_{z\text{-}p}$ levels ranging from 172 to 189 dB re 1 µPa at the same distance (Norro et al., 2013). Even if these emissions are limited in time, they have to be considered of the same order of magnitude as those produced by airguns (ESF. 2008). While piling pin piles seemed to generate less noise than piling larger monopiles, this could not be statistically underpinned. The total number of blows and hence the piling time required for the installation of one jacket, is however higher than for a monopile. When normalized to the installed power, 57% more blows/MW installed were needed for the construction of an average jacket foundation than for a monopile foundation. Most of the energy during piling is present in the 50 Hz to 1 kHz frequency window (computed for several strokes), where several foundation-specific peaks may be discerned (Figure 3).

When normalised to 750 m for the source (Ainslie et al., 2010), the piling of a 5 m diameter monopile and a 1.8 m diameter pin pile generated a maximum $L_{z\text{-}p}$ of 194 dB re 1 µPa, respectively 189 dB re 1 µPa. As comparison, same normalisation is applied to the literature data presented in Nehls et al. (2007), $L_{z\text{-}p}$ ranged from 185 dB re 1 µPa for a 3.3m diameter pin piling event at FINO 2 (Germany) to 196 dB re 1 µPa for a 4.2 to 4.7 m diameter monopiling event at North Hoyle, Scroby Sands and Barrow (UK), and FINO 3 (Germany). A normalised 200 dB re 1 µPa at 750 m was finally obtained for the piling of a 4.7 m diameter monopile at the Q7 wind farm (de Jong and Ainslie. 2008).

Parvin et al. (2006) cited by Nehls et al (2008) derived a relation between $L_{z\text{-}p}$ and the diameter of the pile. When applied for pile of 5m and 1.8 m diameter the $L_{z\text{-}p}$ values obtained at 750 m are respectively 197 dB re 1 µPa and 190 dB re 1 µPa. Good agreement is obtained even if energy produced by the hammer as well as the nature of the sediment are not taken into account explicitly.

Figure 3. 1/3 octave spectra of ambient noise at the Bligh Bank (black), as well as noise emitted during the construction and operation of offshore wind farms. Jacket for a 6,15 MW turbine: construction (red) and operation (blue); monopile for a 3 MW turbine: construction (green) and operation (pink).



The propagation model indicates that noise generated by monopiling attenuated to ambient noise levels at 70 km from the source, while this distance is shorter for pin piling noise (i.e. 50 km; Figure 4). When considering the noise level of major disturbance for harbour porpoises *Phocoena phocoena* of $L_{z\text{-}p}$ 149 dB re 1 µPa (Bailey et al., 2010), according to this model this species would suffer major disturbance up to a distance of 8 km for pin piling and 16 km for monopiling.

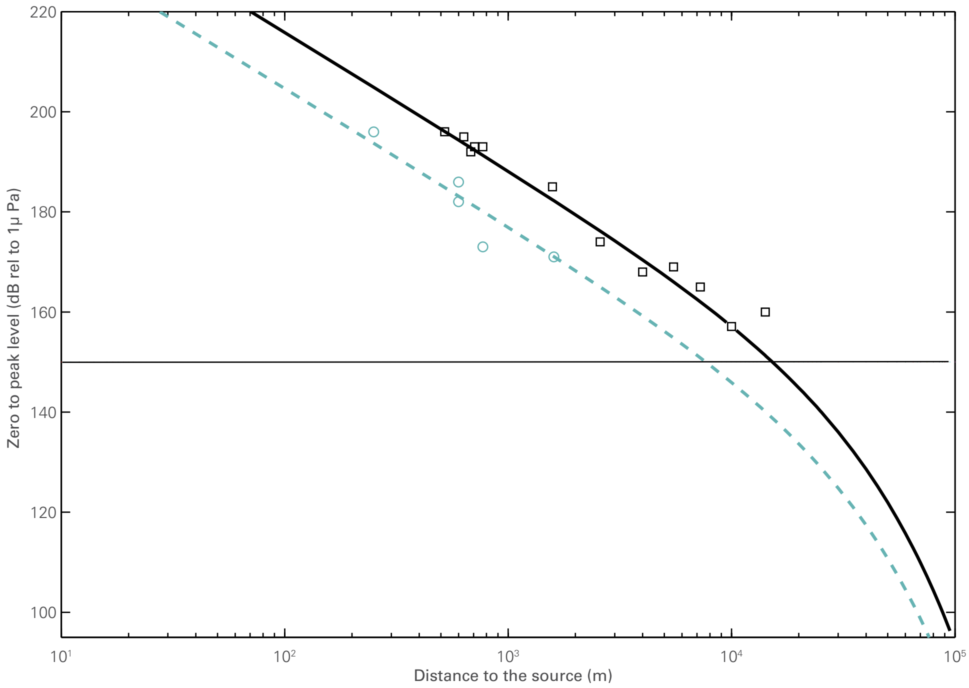


Figure 4. Propagation model derived from pin piling (dashed line) and monopiling (plain line). Squares and circles are the measured $L_{z\text{-}p}$ for monopiles (squares) and jackets (circles) respectively, while the horizontal line at 149 dB re 1 µPa indicates the level ($L_{z\text{-}p}$) for major harbour porpoise disturbance (Bailey et al., 2010).

Because of the expectation of a more limited impact of relatively low level operational noise compared to construction noise, less data exist on the operational noise emitted by operational wind turbines, especially large ones (5 MW or more). Tougaard et al. (2009) based on measurements taken close to the foundation (14 and 20 m) demonstrated an increase above the ambient noise of 10 to 20 dB re 1 µPa at 125 Hz for 2 MW wind turbines, while no increase was detected at other frequencies. Betke (2006) however reported an additional peak in the 1/3 octave spectrum at 150 Hz. In our study, operational noise was measured both for the GBF and jacket foundation wind turbines at the Thorntonbank and the monopile foundation turbines at the Bligh Bank. A 3 MW monopile wind turbine typically generated a sound pressure twice as high as that of a 6.15 MW jacket foundation turbine (i.e. 6 dB re 1 µPa (RMS) higher throughout the 1/3 octave spectrum; Figure 3), in its turn emitting higher noise levels than a 5 MW GBF wind turbine (by 6 dB RMS). Note that during the measurements sea states ranged from 2 to 3, and/or a wind force of 4-5 Beaufort.

LEGISLATION AND NOISE LEVEL LIMITS

With regards to operational above water noise, environmental noise limits for onshore wind turbines are given in VLAREM, in which noise limits depend on the time of the day (i.e. day, evening, night) and the type of area. In the most restrictive conditions (i.e. residential area) the noise should not exceed 39 dB(A) at night. A decision on how to measure onshore wind turbine-generated noise is under construction by the Flemish government. However, detailed calculation guidelines are available. These are based on ISO9613, adverse meteorological conditions, and equivalent levels. If these regulations would be applied to the offshore wind turbines studied, the minimal distance for siting a residence to a single wind turbine would need to be higher than 500 m (at wind speeds below 12 m/s). For a park of 100 wind turbines, this distance would need to be increased to at least 3-4 km. We should however mention that the residential areas nearest to the offshore wind farms are located at a distance of 30 km at present and 21 km when the whole Belgian wind farm zone will be developed. Residents along the Belgian coast will hence never experience noise pollution from the offshore wind farms.

For underwater generated noise, limits are not yet fully implemented in Belgian legislation, but a maximum L_{z-p} of 185 dB re 1 µPa at 750m from the noise source has been recommended in the framework of the implementation of the Marine Strategy Framework Directive (MSFD) (Anonymous, 2012). These underwater noise level limits are of course not directly related to human welfare, but rather to its disturbance of marine life, with currently special attention to marine mammals. Given the seasonally high density of harbour porpoises in Belgian waters (up to more than 2 ind./km² on average), the possible impact of excessive noise on this species is explored in Chapter 7.

FUTURE MONITORING

Next to the weather limitations to perform *ad hoc* noise measurements from an RHIB at sea, the most critical issue to monitor construction noise is the ability to be on site when work is undertaken. At several occasions during the first years of monitoring the piling work was cancelled at short notice, forcing the monitoring team to return to the harbour without performing any measurements. To overcome the above-mentioned difficulties, the future construction noise monitoring will also be performed using moored instruments. These instruments record long time series of underwater noise covering one or more complete sequences of piling. The instruments will also be used for operational noise recordings throughout a wide range of weather conditions, currently problematic given the limitation of a sea-state of 2-3 and/or a 4-5 Beaufort wind force.

Also some questions regarding above water noise produced by large offshore wind turbines remain unsolved. The influence of inflow turbulence on (low frequency) noise emission could be worth studying. For offshore wind turbines, it is expected that it is mostly relevant in the presence of upwind turbines. Slow fluctuations in noise levels may be an issue when it comes to estimating the perception of wind turbine noise. The directivity of this component of the noise is not known very well. Piling noise propagation was calculated using linear propagation models. However, levels are high and propagation distance is long so mild non-linear effects may occur. Measurements at larger distance could validate this influence.

Finally, to comply with the newly proposed guidance document for monitoring underwater noise in European seas (Dekeling et al. 2013), a register of sources and levels of noise should be compiled. The future offshore wind farm noise monitoring programme will therefore start developing a register for underwater noise sources and levels in the BPNS, which will facilitate setting a context for underwater noise interpretation and evaluation.