Bubbles JIP

Bubbles JIP project: efficient and effective use of bubble curtains for noise mitigation in offshore installation projects

WP1: Defining the starting conditions

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Summary

The Bubbles JIP project aims to achieve more efficient and effective use of bubble curtains for noise mitigation in offshore installation projects by improved engineering of the bubble curtain. This report describes work package 1 (WP1) which aims to provide part of the background information for the testing and modeling in WP2, WP4, WP5 and WP6. This is done by collecting and presenting the existing information on noise sensitivity of marine life, noise criteria and influencing environmental conditions, as well as information on current and future offshore wind turbine construction characteristics and noise emission levels provided by the industrial companies involved.

Information was collected by a questionnaire among the Bubbles JIP partners and a literature review. An overview was compiled of the formal offshore piling noise limits of the countries of interest which can be used to indicate the parameter space for the further development of solutions for bubble curtains (also called bubble screens). It is expected that complying with the noise limits for future offshore piling projects (at increasing water depth and pile size) cannot be guaranteed with the current generation bubble curtains. Therefore, contractors require more effective bubble curtains (a practical bubble curtain system solution at minimum cost and emissions), as well as a procedure (or models) for reliable estimation of the achievable noise levels (broadband SELss at 750 m from the pile) with optimized bubble curtains. For those two objectives there is a need for better understanding of the parameters that determine the effectiveness of bubble curtains. These parameters are further specified in a number of conclusions and recommendations.

A bubble curtain reduces underwater sound because underwater sound reflects at the transitions between ‘water’ and ‘bubbly water’ and is absorbed by resonating bubbles. However, the influence of bubble curtain characteristics (diameter of bubble curtain, diameter of bubbles, density of bubbles) on the noise reduction is insufficiently known. This has to be investigated in order to optimize the bubble curtains by adapting the nozzle hose design parameters (e.g. diameter, nozzle shape, size and spacing), hose geometry, air flow and air pressure. Moreover, the effectiveness of bubble curtains depends on local environmental parameters such as water depth and currents and sea floor properties, but the quantitative relations are insufficiently known.

Current bubble screens provide maximum reduction at frequencies (>250 Hz) that are largely above the dominant frequency range for unmitigated impact piling noise (80-400 Hz). Therefore, a shift of the mitigation spectrum of bubble curtains towards lower frequencies would be more efficient in reducing the broadband sound levels. This may be possible e.g. by producing larger bubbles with a lower resonance frequency. However, current generation bubble curtains provide a limited control of the parameters air pressure and volume flow and geometry of the hose (length, distance to the pile, shape). It can be recommended to consider frequency dependence in the modelling of noise exposure, mitigation and sensitivity limits.

Results of the WP1 report will also be used as input to the development of the “Best Practice” (WP7) of the Bubbles JIP project.

1 Introduction

1.1 Background

The Bubbles JIP project aims to achieve more efficient and effective use of bubble curtains for noise mitigation in offshore installation projects by improved engineering of the bubble screen. In that way the noise levels can be better controlled and the risk not to comply with the specific noise requirements per piling project is reduced in a cost-effective manner (Grow project proposal Bubbles JIP).
This work package 1 (WP1) aims to provide part of the background information for the testing and modeling by collecting and presenting the existing information on noise sensitivity of marine life, criteria and influencing environmental conditions, as well as information on current and future offshore wind turbine construction characteristics and noise emission levels provided by the industrial companies involved. This WP is not aimed at providing a complete overview of the state of the art for produced noise levels, mitigation possibilities and effects of impulse noise because that would require a tremendous effort. A comprehensive experience report on piling-driving noise with and without technical noise mitigation measures is recently published by Bellmann et al. (2020). However, the current WP1 report should be sufficient to clarify the necessity and extent of the required reduction of impulsive noise levels and its dependence on the involved regional sea, permitting country, wind turbine and oil & gas pile characteristics, environmental conditions, etc..

1.2 Aim

The aim of WP1 is to:
1. Provide an overview of existing rules and regulations at (future) locations of offshore windfarms.
2. Provide an overview of sensitivities to noise levels and frequency ranges of marine mammals, fish and other marine life at these locations.
3. Provide an overview of typical sound levels during piling and identify parameters which determine sound levels, as well as the current experience with the application of bubble screens to mitigate underwater noise during offshore piling activities.

This result of the WP1 will also be used as input to the development of the "Best Practice" (WP7) of the Bubbles JIP project.

1.3 Methods

The methods applied in this WP1 comprise:

- A questionnaire to the Bubbles JIP partners in order to compile information on the practical situation as well as the experiences and expectations (see chapter 2 and Annex 3).
- A literature review and concise literature search on recent publications.
- Collection of information on recent and ongoing developments in symposia and projects.

2 Questionnaire

In order to compile information on the practical situation as well as the experiences and expectations of the project partners, especially the industrial partners, a questionnaire (Annex 3) was set up and answered by the project partners. The integrated and summarized results are shown in Table 1. The results can be used as starting conditions for other WPs of the Bubbles JIP project.

Table 1 Result of the questionnaire integrated and summarised for each topic

Questions	Response
Construction characteristics	
Hammer type	Hydraulic hammers with energy ratings up to 4000 kJ are currently in use, with larger hammers being developed (up to 5500 kJ), as well as new hammer types (such as BLUE Piling).
Hammer energy	Hammer energies typically lie in the range between 300-4000 kJ. Normally driving is started at low energy setting (200-350 kJ) which increases with deeper pile driving (soft start procedure). With BLUE piling technology the performance is measured by means of max impact force which is 350-600 MN.
Pile size, current and future	There are two typical used piles; jacket piles and monopiles. For jacket piles the size of the piles are normally between 2 and 4 m in diameter and these are driven to 20-90 m penetration. For monopiles the diameter is between 7-11 m and these are driven to 20-65 m penetration. In the future, the diameter and penetration will probably need to be increased (~ 8-12 m diameter) due to driving in deeper water or larger turbine sizes.
For jacket foundations: pre-piling or post-piling	Wind turbines can be founded either on monopiles, or on jacket structures. For jackets like turbine foundations, pre-piling is commonly used. Monopile installation could be seen as pre-piling as well (no acoustic coupling with surrounding structures). For oil&gas structures, wind farm substations and converter platforms, that are normally founded on large jacket structures, post piling is used, whereby the pile is driven through sleeves connected with the jacket structure.
Applied mitigation measures	For applied mitigation measures, the IHC noise mitigation system (NMS), the Offnoise Hydro-Sound-Damper-System (HSD) and single and double big bubble curtains (BBC and DBBC) are commonly used. Furthermore, new piling techniques (e.g. BLUE piling) and small-scale bubble curtains are used in some cases. Hammers with noise reducing add-ons are under development, for example: IHC Hydrohammer S-4000 including Pulse technology. MENCK has a similar technology underway, the MNRU (MENCK Noise Reduction Unit). These add-ons shift the frequency spectrum more to the lower frequencies, but the noise reduction has not yet been demonstrated in (offshore) tests.
Typical frequency range and noise level during piling	Typical sound levels emitted by a single strike are around 170-180 dB SEL at 750 m distance, without mitigation. With mitigation this can be reduced by 10-20 dB. As for peak frequency ranges; they are stated between 80-400 Hz.
Environmental conditions	
Water depths	The water depths at which current drivings are performed with bubble curtains lie between 20-55m depth.
Mean current speed	Mean water current speed at driving locations is around 0.5 m/s, and 1.0 m/s at maximum.
Sea floor characteristics	Sea floor characteristics at which driving take place generally consist out of soft sand, clay sand or silt (complete or only top layer).
Distances to coast	Drivings are stated to take place in a range from 2 to 50 km (or more) from the coastline.
Regional seas and involved countries	The industrial partners in this project are involved in Germany, UK, Denmark, Netherlands, Belgium, France, USA, Taiwan, Japan and South Korea.

Experience and expectations	
Current experience with the application of bubble screens Expected limitations for future effective mitigation by bubble screens	Project partners state different experiences and limitations with the application of / mitigation by bubble screens for now and in the future and therefore these are combined and listed below: • Limitations are to be expected for the bubble generation system in combination with the environmental conditions. • Influence of bubble curtain characteristics (diameter of bubble curtain, diameter of bubbles, density of bubbles) on the noise reduction is insufficiently known. • Hose geometry and air pressure can be used to optimize the screen. But we do not yet know how, and regulators do not always allow modifications to the current practice. • The effectiveness of bubble screens depends on air distribution over the water depth. • Air flow from compressors can be a limiting factor as well as air flow that is possible to get through the currently used hose diameters. • With increasing pile sizes and hammer energy sufficient reduction by bubble screens may become more difficult. • Due to the large size of piles, which are still increasing, bubble screens are yet not effective enough. • With currents above 0.5 m/s the bubble curtain will get dispersed, losing its effectiveness. But we don't yet know to what extent. • With currents above 1 m/s the deployment vessel could not be able to sail around the planned trajectory. • Water depth increase beyond 50 m may be a limitation for bubble screens because the hydrostatic pressure could become too high to get bubbles out of the nozzle hose at current operation pressures. • Sound propagation via the sediment layers under a bubble screen is a limiting factor. • Large operational costs compared to already applied reductions. • CO_2 emission by compressors is a concern; fuel savings by more efficient bubble curtains can contribute here. • When using different vessels, (for pre-laying hoses, surveying hose locations, and others like MMO vessels, PAM vessels etc.) safety and navigational risks may be applicable. • When deploying the hose without air, some twisting and bending may occur, however when deploying the hose with air, floatation due to low weight causes difficulty getting the hose to the sea floor. • BBC's need to be pre-laid to avoid waiting time of the installation vessel, so more BBC's are needed in order to prepare for subsequent locations already. • A single bubble screen is often not enough to comply to noise reduction requirements. • Because modelling is very complex and empirical results of noise reduction with bubble screens have a lot of variation, it is hard to determine and prove whether the proposed/chosen noise mitigation system will ensure compliance to noise reduction requirements. • With increasing pile diameter and water depth, DBBC will likely not be sufficient to comply to noise reduction requirements. Addition of a 3rd or 4th bubble screen is not a feasible option: additional noise reduction is minimal, while logistical challenges, costs and CO2 emission increase significantly. • Difficult to predict BBC effectiveness in unprecedented cases, such as with increasing pile diameter or water depth.

3 Piling noise metrics

According to the ISO 18405 standard for underwater acoustic terminology, sound is an *alteration in pressure, stress or material displacement propagated via the action of elastic stresses in an elastic medium and that involves local compression and expansion of the medium, or the superposition of such propagated alterations*. Hence, sound can be observed in terms of pressure fluctuations as well as in terms of fluctuations in displacement, velocity or acceleration of 'sound particles' (defined as the *smallest element of the medium that represents the medium's mean density*). In a uniform medium, far away from sound sources and boundaries, pressure p and particle velocity v are linearly related by the characteristic impedance $Z = \rho c$ of the medium, with ρ the density and c the speed of sound in the medium. Closer to sources and boundaries such as sea floor and water surface, the linear relationship $p = Zv$ does not hold. The speed of sound in sea water is $c \approx 1490\,\mathrm{m/s}$ at atmospheric pressure, temperature $10°\mathrm{C}$ and salinity 35 ppm and varies with pressure, temperature and salinity. The density of seawater is $\rho \approx 1027\,\mathrm{kg/m^3}$.

Many marine animal species explore their environment through some form of hearing (see Chapter 4). Marine mammal ears are sensitive to sound pressure, while the 'ears' of fishes and invertebrates are more sensitive to sound particle motion (Popper & Hawkins, 2018). The measurement of underwater sound pressure with hydrophones is well established. The measurement of underwater sound particle motion is relatively new, and standards procedures are lacking.

If the received sound pressure p as a function of time t is described by a function $p(t)$, expressed in pascals, the peak sound pressure p_{pk} is defined as the greatest magnitude of the sound pressure during a specified time interval T:

$$p_{\mathrm{pk}} = \max\{|p(t)|\}_{t=0}^{t=T} \quad \text{[Pa]} \qquad (1)$$

The associated (zero-to-) peak sound pressure level in defined as

$$L_{p,\mathrm{pk}} = 10\log_{10}\left\{\frac{p_{\mathrm{pk}}^2}{p_0^2}\right\} \quad \text{[dB re 1 μPa}^2\text{]} \qquad (2)$$

with reference pressure $p_0 = 1\,\mathrm{\mu Pa}$.

The sound exposure level (SEL), is defined as:

$$L_E = 10\log_{10}\left\{\frac{\int_{t=0}^{t=T} p^2(t)\mathrm{d}t}{p_0^2 t_0}\right\} \quad \text{[dB re 1 μPa}^2\text{s]} \qquad (3)$$

with reference exposure $p_0^2\mathrm{t}_0 = 1\,\mathrm{\mu Pa^2 s}$.

The duration of the transient sound is given by the selection of a sub-window that contains 90% of the total cumulative exposure in the signal. The start and end times of this sub-window (t_5 and t_{95}) are determined by the moments at which the cumulative exposure reaches 5% and 95% of the total exposure, as illustrated in Figure 1.

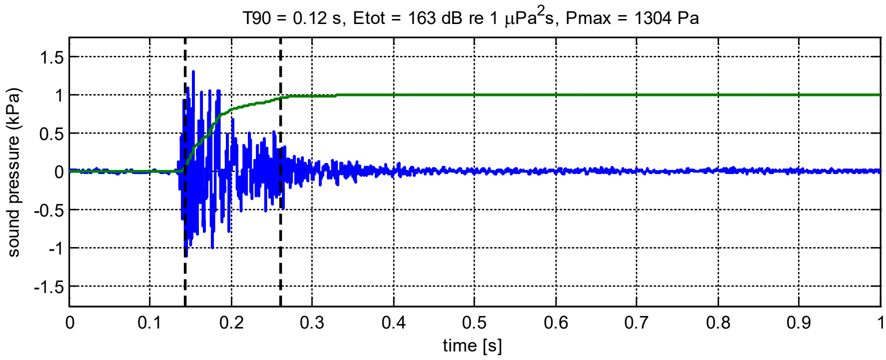

Figure 1 Example of the acoustic pressure received at a hydrophone for a single piling strike (blue line). The green line gives the cumulative sound exposure as a function of time (scaled to an arbitrary reference level). The thick black dashed lines indicate the t_5 and t_{95} start and end times of the T_{90} (T90) window. The peak sound pressure (Pmax = p_{pk}) is defined as the maximum of the absolute value of the pressure signal within the T_{90} window and in the complete frequency bandwidth of the recording. The sound exposure level (Etot = L_E) is the total energy in the T_{90} window.

Sound exposure can be quantified for each individual piling strike (single strike SEL; SEL_{ss}) as well as for a specified time duration including a series of piling strikes (cumulative SEL; SEL_{cum}). Where noise limits are set for single strike SEL (see Chapter 5), the statistics of the SEL's for the complete series of strikes for the installation of a pile needs to be recorded. Some nations apply the limit to the maximum SEL in the series, others allow exceedance for a small percentage of the strikes and apply the limit to e.g. the 5% exceedance level of the series ($SEL_{5\%}$).

Different marine species are sensitive to sound exposure in different frequency ranges (see e.g. Slabbekoorn et al., 2010). These different sensitivities can be considered by applying an auditory frequency weighting in the calculation of the acoustic metrics, see (see Chapter 4). Also, acoustic measurements of sound pressure or sound particle motion may be subject to the frequency characteristics of the measurement equipment. Hence, it is important to specify the applied frequency weighting when reporting underwater sound metrics. Note that the current noise limits set by regulation (see Chapter 5) apply to unweighted sound exposure levels, although suggestions are being considered (e.g. Dähne et al., 2017) that noise regulation should be based on frequency-weighted sound levels, because these could give a more appropriate description of the effectiveness of mitigation measures, such as bubble screens, for protecting marine species that are not very sensitive to low frequency sound, such as harbour porpoises.

International standard ISO 18406:2017 (Underwater acoustics — Measurement of radiated underwater sound from percussive pile driving) specifies how to measure the acoustic metrics for offshore piling projects.

It should be noted that sound levels in decibels under water are not comparable with decibels above water (in air).

4 Sensitivity of marine life to impulse noise

This chapter provides an overview of sensitivities to noise levels and frequency ranges of marine mammals, fish and other marine life. First, an introduction to general aspects of sound hearing ability and response types of animals is given.

The sensitivity of marine life to impulsive noise depends on a species' ability to hear a sound and the impact the sound has on a species. A species' sensitivity to a certain sound is shaped by the type of sound (sound waves or particle motion) the species can process, the species' ability to hear certain frequencies and the species' auditory thresholds. In general, for a certain species, auditory thresholds - the sound level above which a sound is audible- are frequency specific; the auditory threshold is lowest for the frequencies a species is most sensitive to, and infinite for frequencies inaudible for this species, see some representative audiograms in Annex 1.
When sound affects reception of acoustic signals of interest or sound affects an animal in such a way that normal behaviour is disrupted it is qualified as noise (Richardson et al., 2013). Grosso modo, the effect of sound on animals diminishes further away from the sound source, due to geometrical spreading and attenuation of sound. Depending on the distance and sound level, sound might have a different effect on animals (Gordon et al., 2003), categorized by different impact zones (Richardson et al., 1995):

1. *Zone of Audibility*. In this zone the sound or noise will be audible to the marine animal.
2. *Zone of Masking*. In this region the noise interferes with the animal's ability to perceive (detect, interpret, and/or discriminate) relevant sounds.
3. *Zone of Avoidance*. The region where noise induced behavioral changes are likely to occur in marine animals, such as swimming away from the source to avoid the sound exposure.
4. *Zone of Injury*. The region where noise induced physical damages are likely to occur. Exposure in this region causes physical injury and/or temporary hearing loss (Temporary Threshold Shift, TTS) or permanent hearing loss (Permanent Threshold Shift, PTS) both depending on the time of the exposure and the exposed level.

These impact zones are not sharply defined, and zones will overlap depending on the conditions (e.g. background noise level, physiological status of an individual animal). The risk of injury depends on the duration of the sound exposure as well as on the sound level.

4.1 Noise sensitivity of marine species

To regulate the impact of noise on marine species, policy makers use certain species as indicator for changes in the marine environment and set thresholds to the sound exposure of these species. To identify noise sensitive species as indicator for changes in noise exposure, HELCOM (2017) and von Benda-Beckmann et al. (2020) used a set of selection criteria:
1. Hearing sensitivity
2. Impact of noise
3. Threat status
4. Commercial value
5. Data availability

Other regional sea organisations like OSPAR use a comparable set of selection criteria. For our purpose (to identify the species most sensitive for impulse noise) the first two (and fifth) criteria are relevant. All five criteria can be used to select species relevant for regulations to minimize noise impact on the marine environment (see chapter 5). In sections 4.2 and 4.3 we will describe the hearing sensitivity of marine mammals and other taxa.

4.2 Marine mammals

An overlap between the frequency range of the hearing sensitivity of an individual/species and the frequency range of a sound source determines whether or not an individual is able to detect and respond to a sound, or can experience damage to auditory organs. Differences in behavioural responses observed among functional hearing groups may not solely result from hearing capabilities, but possibly also from other taxon-specific factors. For several years the review by Southall et al. (2007) was commonly used as standard to assess marine mammal species' sensitivity to sound. This review resulted in noise exposure criteria within a framework that (1) categorized marine mammals into functional hearing groups based on what was known about their hearing, (2) distinguished noise types with differing potential to affect hearing based on acoustical characteristics, and (3) used multiple sound exposure metrics to account for sound properties which were expected to have the greatest influence on hearing. Southall et al. (2007) mainly focused on hearing effects (TTS/PTS). However not all regulators consider TTS to be an injury and disturbance of animals by noise is seen as highly relevant. Threshold values for disturbance are less well established as thresholds for TTS and PTS but nevertheless highly relevant for the European regulation and noise limits.

After publication of Southall et al. (2007) several weighing functions were developed to account for frequency-dependent effects of noise for the different marine mammal hearing groups. Finneran & Jenkins (2012) introduced the Type-II filter for high frequency cetaceans, which includes the harbour porpoise. Other weighing functions are described in Dekeling et al. (2014), Finneran (2015, 2016), Tougaard et al. (2015) and Von Benda-Beckmann et al. (2015). These weighing functions and other advances in the knowledge on marine mammal hearing have allowed refinement of the Southall et al. (2007) noise exposure criteria (Southall et al., 2019).

Southall et al. (2019) categorized marine mammals in groups based on functional hearing: Low-frequency cetaceans, high-frequency cetaceans, very high-frequency cetaceans, sirenians, phocid carnivores and other marine carnivores (Table 2). These groups are described in sections 4.2.1 to 4.2.6. For each group mean absolute and normalized (to the frequency of best hearing) audiograms were estimated, by fitting respectively available original and normalized thresholds with the function. It should be noted that species specific audiograms typically are less broad than the group audiograms. Due to a lack of data on hearing thresholds a different approach was used for the group of low-frequency cetaceans.

To get a grip on noise impact on members of each hearing group, temporary hearing loss (Temporary Threshold Shift, TTS) is modelled. TTS depends on the duration of the sound exposure and the exposed sound level. At frequencies where an animal has its sensitive hearing (i.c. low auditory thresholds) it is more sensitive to effects of sound exposure than for frequencies for which the animal's hearing is less sensitive. The available hearing data, which formed the basis for the group audiograms, were used to construct group specific weighing functions (see above) and noise exposure functions. The latter shows the exposure levels for TTS or PTS-onset in relation to frequency.

TTS-onset was defined as a TTS of 6 dB extrapolated from available data or measured shortly (1-4 min) after cessation of the sound exposure (following Southall et al., 2007). PTS-onset is defined as a shift of 40 dB after sound exposure and is extrapolated from other mammal studies (Richardson et al., 1995). A sound exposure level of 15 dB above the threshold value for TTS is assumed to be the exposure threshold for PTS onset. For VHF and HF cetaceans both TTS- and PTS-onset for impulse sound can be calculated based on data. TTS and PTS-onset for other hearing groups is based on more assumptions (see Southall et al., 2007, 2019). Southall et al. (2019), however, emphasized: "It should be recognized that for all groups, these are estimated functions based on data from a few species and individuals. These curves represent the best fit to the limited existing data based on the assumptions and procedures described herein, but it should be clearly recognized that most species within each group have not been directly tested."

Table 2. Proposed marine mammal hearing groups and applicable auditory weighing functions (Southall et al., 2019)

Marine mammal hearing group	Auditory weighting function	Genera (or species) included
Low-frequency cetaceans	LF	Balaenidae (*Balaena*, *Eubalaenidae* spp.); Balaenopteridae (*Balaenoptera physalus, B. musculus*)
		Balaenopteridae (*Balaenoptera acutorostrata, B. bonearensis, B. borealis, B. edeni, B. omurai; Mageptera novaeangliae*); Neobalenidae (*Caperea*); Eschrichtiidae (*Eschrichtius*)
High-frequency cetaceans	HF	Physeteridae (*Physeter*); Ziphiidae (*Berardius* spp., *Hyperoodon* spp., *Indopacetus, Mesoplodon* spp., *Tasmacetus, Ziphius*); Delphinidae (*Orcinus*)
		Delphinidae (*Delphinus, Feresa, Globicephala* spp., *Grampus, Lagenodelphis, Lagenorhynchus acutus, L. albirostris, L. obliquidens, L. obscurus, Lissodelphis* spp., *Orcaella* spp., *Peponocephala, Pseudorca, Sotalia* spp., *Sousa* spp., *Stenella* spp., *Steno, Tursiops* spp.); Montodiontidae (*Delphinapterus, Monodon*); Plantanistidae (*Plantanista*)
Very high-frequency cetaceans	VHF	Delphinidae (*Cephalorhynchus spp.; Lagorhynchus cruciger, L. austrailis); Phoconidae (Neophocaena* spp., *Phocoena* spp., *Phocoenoides*); Iniidae (*Inia*); Kogiidae (*Kogia*); Lipotidae (*Lipotes*); Pontoporiidae (*Pontoporia*)
Sirenians	SI	Trichechidae (*Trichachus* spp.); Dugongidae (*Dugong*)
Phocid carnivores in water Phocid carnivores in air	PCW PCA	Phocidae (*Cystophora, Erignathus, Halichoerus, Histriophoca, Hydrurga, Leptonychotes, Lobodon, Mirounga* spp., *Monachus, Neomonachus, Ommatophoca, Pagophilus, Phoca* spp., *Pusa* spp.)
Other marine carnivores in water Other marine carnivores in air	OCW OCA	Odobenidae (*Odobenus*); Otariidae (*Arctocephalus* spp., *Callorhinus, Eumetopias, Neophoca, Otaria, Phocarctos, Zalophus* spp.); Ursidae (*Ursus maritimus*); Mustelidae (*Enhydra, Lontra feline*)

4.2.1 Low-frequency (LF) cetacean hearing group

The low-frequency group contains all mysticetes or baleen whales (Table 2). Although the hearing capability of baleen whales has not been measured yet, indirect studies indicate an audible frequency range from 7 Hz (5–20) to 20–30 kHz (Table 3). Within the group some species (e.g. Blue and Fin whale) may have a higher low-frequency sensitivity than others (e.g. Humpback, Minke whale), and may form a distinct group. There is, however, not enough data available to justify a subdivision of this group. Species in this group are therefore assigned a single weighing function: the so-called LF weighing function.

Despite the lack of data, TTS-onset is derived using the group specific audiogram, and estimated LF weighting function and noise exposure curve (*Figure 10* in Annex 2). TTS is estimated to occur at a SEL of 168 dB re 1μPa^{2}s (Table 3).

4.2.2 High-frequency (HF) cetacean hearing group

The high-frequency (HF) cetacean hearing group contains most dolphin species (e.g. Bottlenose dolphin, common dolphin and pilot whale), beaked whales, sperm whales and killer whales (Table 2). This group was called mid-frequency (MF) cetacean hearing group in the reviews by Southall et al. (2007) and National Marine Fisheries Service (2018). Hearing sensitivity has been measured for approximately one third of the species in this group (n = 11). From the available data an audible frequency range from 150 Hz to 160 kHz is derived (Table 3). The best hearing sensitivity of members of this group lies around 55-58 kHz as shown in the group audiograms (*Figure 4*, *Figure 5*, *Figure 10*).
Combining the HF group audiogram, HF weighting function and noise exposure curves (*Figure 10*) a TTS-onset of 170 dB re 1μPa^{2}s is calculated for high-frequency cetaceans. The associated PTS is calculated by adding 15 dB to the TTS-value (185 dB re 1μPa^{2}s Table 3).

4.2.3 Very high-frequency (VHF) cetacean hearing group

The very high-frequency (VHF) cetacean hearing group contains porpoises, most river dolphins, pygmy and dwarf sperm whale and a number of oceanic dolphin species from the southern hemisphere (Table 2). Direct measurements of hearing ability are available for harbour porpoise and Amazon river dolphin and indicate higher upper-frequency hearing limits than HF species. An audible frequency range from 275 Hz to 160 kHz is derived (Table 3), with the most sensitive frequencies above 100 kHz as shown in the combined group audiograms (*Figure 4*, *Figure 5*, *Figure 10*). Echolocation signals exceed 150 kHz in some species, representing the highest frequencies of all marine mammals.
TTS measurements are available for VHF cetaceans, in fact harbour porpoise is one of the best studied animals. A review is conducted by Heinis et al. (2015) including the derived threshold value for sensitivity of this species for disturbance (avoidance) by impulse noise.
Combining the VHF group audiogram, VHF weighting function and noise exposure curves (*Figure 10*) a TTS-onset of 140 dB re 1μPa^{2}s SEL is calculated. The associated PTS is calculated by adding 15 dB to the TTS-value (155 dB re 1μPa^{2}s (Table 3).

4.2.4 Sirenian (SI) hearing group

The sirenian (SI) hearing group contains manatees and dugongs (Table 2). Based on the anatomy of the hearing sensors it was predicted that the hearing range extends from infrasound frequencies to less than 20 kHz with a peak sensitivity around 8 kHz. Direct hearing measurements of West Indian manatees, however, indicate an upper level of 60 kHz. Though no audible frequency range is presented by National Marine Fisheries Service (2018, Table 3), estimated group audiograms were derived from these data (Figure 6 in Annex 1). TTS measurements are unavailable for sirenians. Therefore TTS-onset criteria are derived based on the group specific audiogram (Figure 6) and estimated weighting function and noise exposure curve (*Figure 11*). TTS is estimated to occur at a SEL of 175 dB re 1μPa^{2}s (Table 3).

4.2.5 Phocid carnivores in water (PCW) hearing group

The phocid carnivores in water (PCW) hearing group contains all true seals and the Antarctic and Arctic ice seals (Table 2). One of their anatomical characteristics distinguishing them from otariid seals is the lack of outer ear structures. As amphibious animals, members of this group can hear both in air and under water. This section will focus on underwater hearing capability and sensitivity only. The morphological adaptations in their ear structure allows them to expand their frequency range of hearing in water. Group audiograms were based on data of four species: northern elephant seal, harbour seal, spotted seal and ringed seal (Figure 7, Figure 8). Phocid carnivores have the broadest range of best hearing of all pinnipeds, with the best hearing frequency around 10 kHz and an upper-frequency exceeding 60 kHz in most species.
Since TTS data are unavailable for the PCW group TTS-onset criteria were derived (*Figure 12*) using the same method as for the SI group, resulting in an estimated SEL of 175 dB re 1μPa^{2}s, and a PTS-onset of 190 dB re 1μPa^{2}s (Table 3).

4.2.6 Other marine carnivores in water (OCW) hearing group

The OCW hearing group includes all non-phocid marine carnivores: Otariid seals (sea lions, fur seals), walruses, sea otter and polar bear. Otariid seals (and other group members) have outer ear structures that distinguish them from the phocid seals. Auditory data are available for five species, and the constructed group audiograms show that species within this group have a less sensitive high frequency hearing than phocid seals (Figure 7, Figure 8). The estimated TTS-onset for this group *Figure 12*) is the highest of all marine mammals, with a SEL of 188 dB re 1μPa²s (Table 3).

Table 3. Auditory characteristics of marine mammal hearing groups. The generalized hearing range is a composite of all species within the group and is based on ca 65 dB threshold from normalized composite audiograms (National Marine Fisheries Service, 2018). TTS threshold is determined from the minimum value of the auditory exposure function and the weighing function at its peak (Southall et al., 2019)

Hearing group	Generalized hearing range	TTS onset SEL (weighted)	PTS onset SEL (weighted)
Low-frequency (LF) cetaceans	7 Hz-35 kHz	168 dB re 1μPa²s	183 dB re 1μPa²s
High-frequency (HF) cetaceans #	150 Hz-160 kHz	170 dB re 1μPa²s	185 dB re 1μPa²s
Very high-frequency (VHF) cetaceans	275 Hz-160 kHz	140 dB re 1μPa²s	155 dB re 1μPa²s
Sirenians (SI)	N/A	175 dB re 1μPa²s	190 dB re 1μPa²s
Phocid carnivores in water (PCW)	50 Hz-86 kHz	170 dB re 1μPa²s	185 dB re 1μPa²s
Other marine carnivores in water (OCW)	60 Hz-39 kHz	188 dB re 1μPa²s	203 dB re 1μPa²s

Note that High-frequency cetaceans were called Mid-frequency cetaceans in Southall et al. (2007) and National Marine Fisheries Service (2018).

N/A: not available.

4.3 Other marine species

Fishes and seabirds form important ecological groups of marine ecosystems. Therefore, effects of noise on these species can have profound effects on the system. However, knowledge on the hearing sensitivity and the effect of noise is limited.
Defining hearing sensitivity in fish is complex, since species have adapted differently to particle motion and sound pressure (Radford et al., 2012). Both sound components should be considered to quantify fish hearing sensitivity and their sensitivity to sound, but this is challenging. Recent reviews of the current knowledge on the impact of sound on fish are Popper et al. (2019) and Popper & Hawkins (2019).

Fish have a high variability in morphological adaptations to perceive sound, but they are generally classified as hearing generalists or hearing specialists (Popper et al., 2003). Hearing generalists are fish species without swim bladder or with a reduced swim bladder (such as flatfish). They tend to have a low auditory sensitivity detecting sound up to about 1 kHz. This sensitivity is mainly related to the particle motion component of a sound field (Fay & Popper, 2012). Hearing specialists have fully functional swim bladders. These species can detect particle motion, but their hearing is more sensitive with generally lower hearing thresholds and a broader hearing range of sounds above 1.5 kHz, but depending on their anatomy their sensitivity for various frequencies varies greatly between species. They are also considered to be more susceptible than hearing generalists to injury due to impulsive sound (e.g. Fay & Popper, 2012; Popper et al., 2019).

Bird sensitivity to sound in air has been shown for a broad spectrum of species under many different circumstances, with a focus on terrestrial species (e.g. Dooling, 2002; Dooling & Popper 2016). In general, bird taxa show less variation in hearing sensitivity than among members of other vertebrate groups. The hearing range of birds exceeds from about 0.5-6.0 kHz. The most sensitive frequency range is 2-3 kHz, with absolute sensitivity often approaching 0-10 dB SPL (Dooling, 2002. Studies on bird sensitivity to underwater sound are limited to a few taxa of diving birds, of which penguins are among the best studied taxa (Wever et al., 1969; Woehler, 2002; Pichegru et al., 2017; Sørensen et al., 2020). The hearing of turtles is poorly understood, but their hearing thresholds have been measured in air and under water using auditory evoked potentials (AEP: Willis, 2015). Logger head turtle (*Caretta caretta*) is the sole sea turtle that has been measured, by both behavioural and AEP methods that showed a similar frequency response (Martin et al., 2012). Behavioural sensitivity showed the lowest thresholds between 100 and 400 Hz, with thresholds at about 100 dB re 1 μPa. AEP measurements on the same individual were up to 8 dB higher. Experiments on their vulnerability to anthropogenic noise, however, are lacking (Popper et al., 2019).

4.4 Concluding remarks

There is not much known on hearing sensitivity of marine fauna. Even for the relatively well studied marine mammals not only a low number of species is tested, but low numbers of different individuals per species are studied as well. Consequently, the data at present are inadequate to support an analysis of variance of the group audiograms. The derived TTS- and PTS-onset criteria at best are temporary until additional data on hearing sensitivity and TTS/PTS measurements will become available.

In other words, for marine mammals, zone of audibility and zone of injury can only be defined with assumptions and knowledge/data gaps. However, information on sound levels in the zone of masking and zone of disturbance is completely lacking, except for harbour porpoises. Disturbance and avoidance of harbour porpoise was studied during construction of wind farms (e.g. Brandt et al., 2016; Geelhoed et al., 2018). Regulation is based on those studies (Heinis et al., 2015, 2019ab).

5 Regulations, rules and criteria

This chapter presents an overview of existing rules and regulations for sound in the North Sea and other areas in the world at (future) locations of offshore windfarms. These rules and regulations are not only based on a species sensitivity to sound, but on other criteria as well, like occurrence in the area of jurisdiction or threat status of a species (see 3.1). Potential effects of pile driving sound on marine mammal species can only occur in areas that spatially or temporally overlap with the distribution of these species. Consequently, mainly species that occur in relatively shallow seas are potentially affected by the impulsive noise; e.g. porpoises, phocid seals, and sirenians. However, with windfarms being planned further offshore, e.g. in the US there is concern for North Atlantic right whale and the Northern resident killer whale during monopile installations.
There are differences in the monitoring and mitigation guidelines among countries. Some guidelines are clearly described in nationally accepted documents, whilst others are issued on a project basis. Some guidelines are described for EIA requirements, whilst others are focused on the different phases of offshore windfarm development. There are, however, broadly two approaches in mitigation of noise exposure on marine mammals: 1) deter marine mammals in an area around the sound source, and 2) limit sound emission in the area around the sound source. Most countries that apply the second approach use species specific thresholds for either disturbance/avoidance or temporarily (TTS) or permanent injury (PTS) in their regulations.

5.1 Europe

In Europe different countries have different approaches.

Some European countries like Denmark, Germany, The Netherlands and Belgium limit sound emission and set thresholds on (broadband) sound emission around pile driving locations (Table 4). Germany has the most stringent noise criteria following their so-called Schallschutzkonzept (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, 2013). The actual criteria are defined in letters from federal authorities to developers. The Schallschutzkonzept (“soundproofing concept”) explains the background, and it also defines a method to come to modified acceptable sound level limits when working near nature reserves. The exact definitions of the thresholds vary per country; Germany and The Netherlands use SEL (sound exposure level) for single strikes, whereas Denmark uses a cumulative SEL. A Danish guideline for underwater noise by installation of impact-driven piles is available (Energistyrelsen, 2016).

- GE-limit $SELss_{5\%}$(750m) = 160 dB re 1 μPa^2s and Lzp(750m) = 190 dB re 1 μPa^2
- BE limit Lzp(750m) = 185 dB re 1 μPa^2 (according to Belgische staat, 2012).
- NL standard SELss(750m) per wind energy area, as adopted in site decisions and calculated in the same way (using the calculated relationship between harbour porpoise disturbance days and population decline) for the farms dating from after the SER agreement. After 2023, the sound limit is fixed to SELss(750m) = 168 dB re 1 μPa^2s for all NL projects.
- In Denmark the cumulative sound exposure level (SELcum) of animals is used as acoustic indicator which needs to be limited to 190 dB re 1μPa^2s for a complete pile driving sequence.

Among these countries there are different ways in evaluation of a SEL. Selection of the maximum SEL of all strikes on a pile (The Netherlands), or selection of the 5% exceedance value, which filters out any chance outliers (Germany). These SEL values are determined on a fixed distance (750 m) from the pile at a fixed elevation, and therefore easy to compare with measured or modeled data. Denmark chose to consider cumulative noise exposure for a swimming animal which requires assumptions like swimming speed and interpretation of the sound distribution levels. Additional to the noise reduction measures these countries prescribe acoustic deterrence measures, soft starts of piling, or have seasonal restrictions to pile driving activities.

For environmental impact assessments and appropriate assessments for future Dutch offshore wind energy projects, The Netherlands prescribes a staged procedure to quantify the effects of marine piling noise on marine mammal populations, specifically on harbour porpoises. This procedure was developed by an expert group (Heinis et al., 2015 & 2019ab). The noise limits for wind farm construction in Dutch waters are derived from this approach. They are specified in terms of a single strike SEL limit, that must be met for all strikes. Until 2023 this limit depends on the season and the number of piles to be installed per wind farm, after 2023 a single, year-round threshold value SEL = 168 dB re 1 μPa^2s at 750 m from the pile will apply.

The UK uses the approach to deter marine mammals in a wind farm construction area before pile driving starts by using ADD-devices, and during the start of pile driving with a 20-minute soft start procedure and does not set thresholds for sound exposure of marine mammals. This is combined with a pre-piling search for protected species, either visually or acoustically, and piling will be postponed if an individual is observed within the monitoring zone. However, for the protection of certain special areas of conservation (SACs) at sea there is a criterion for exposure to underwater sound. Max. 20% of harbour porpoises is allowed to be disturbed every day in a SAC (JNCC, 2010).

European governments aim to harmonize the parameters and criteria for noise. In the monitoring guidance for underwater noise in European seas (Dekeling et al., 2014) a SEL_0 = 140 dB re 1 μPa^2s as a threshold was proposed for significant behavioral disturbance due to multiple explicitly impulsive sounds. The monitoring guidance is to be updated in 2020.

For the purpose of the aim in the current project to investigate and optimize the application of bubble curtains in order to meet noise thresholds it can be concluded that there are different noise thresholds per EU member state (see Table 4 in section 5.5).

5.2 USA

In the USA a mix of the fore mentioned approaches is applied depending on the outcome of project-specific Environmental Impact Assessments. Guidelines to mitigate effects of noise exposure are project-based and require an impact assessment that qualifies the impact on populations of specific protected species. So, the USA has no general sound limits. For marine mammals the Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (National Marine Fisheries Service, 2016 & 2018) are leading. These guidelines include acoustic thresholds (following Southall et al., 2007) as one of the tools to evaluate and mitigate effects of an activity. These thresholds are for species-specific frequency weighted received sound levels to which the animals are exposed. Other tools are behavioral impact thresholds, auditory masking assessments, evaluations to help understand the effects of any particular type of impact on an individual’s fitness, population assessments, etc. Depending on the expected impact a whole suite of mitigation measures needs to be applied to reduce the impact. This involves a procedure with a sound level map that is overlain with the population density of the considered species, to arrive at an expected number of affected individuals.

In the light of the application of bubble curtains it can be concluded that:
- there is no single valued threshold to meet;
- requirement to be able to calculate sound maps (including the effect of mitigation measures) for the different sound metrics is related to different impacts on different species.

5.3 Asia

Asian countries have no overarching rules. Taiwan has a concise set of requirements, while other Asian countries do not. Within countries there may be a lack of standard rules, but an Environmental Impact Assessment or equivalent legislation may impose project specific rules. In some countries the mitigation standards from the main contractor's country need to be followed, e.g. Australian companies operating in Asia have to abide by Australian environmental mitigation standards.
Vietnam follows the Dutch environmental mitigation rules (Table 4).
Taiwan uses a mix of UK and German rules. Taiwan adopted the German noise criteria with some deviations and moreover, these rules are currently undergoing review. Taiwan applies a very strict approach with a maximum SEL value of 160 dB (without applying 5% exceedance), measured at 4 points at 750m distance (in 4 directions), in combination with 24hr marine mammal observer (MMO) and passive acoustic monitoring (PAM). This is in intensive development. Projects that were carried out in 2020 have to meet very different requirements than projects in 2021 (Marco Huisman, Heerema Marine Contractors, pers. com.).

In the light of the application of bubble curtains it can be concluded that for the Asian countries of interest see the European regulation and sound limit values in Table 4.

5.4 Developments

Governments within Europe aim to harmonize the parameters and criteria for noise, but that appears to be a difficult process. There are some publications dealing with comparison of noise criteria (e.g. Pondera Consult, 2014; Scholik-Schlomer, 2015).

Updates of previous guidelines are in progress and due 2020. These updates are developed by EU TG Noise and OSPAR ICG Noise.

The Netherlands has developed the assessment of underwater noise in a larger framework the so-called Kader Ecologie en Cumulatie (KEC) (Heinis et al., 2019a). This KEC is a living document and is improved and adjusted. In the update of the KEC attention should be given to frequency weighing of underwater sound. For the weighing of sound, a method is developed by Southall et al. (2007, 2019) and applied for regulations and rules by the USA.

5.5 Overview and concluding remarks

In this section an overview of the threshold values for underwater sound is compiled partly based on the information on sound limits in the preceding sections and supplied by information on monitoring and mitigation (Table 4).

Table 4 Summary of piling sound limits

Country	Piling sound limit
Germany	Max. unweighted $SEL_{ss,5\%}$ ($L_{E,5\%}$) at 750 m = 160 dB re 1 μPa²s Max. $L_{p,pk}$ at 750 m = 190 dB re 1 μPa
Denmark	Max. unweighted SEL_{cum} for fleeing animals = 190 dB re 1 μPa²s
Belgium	Max. $L_{p,pk}$ at 750 m = 185 dB re 1 μPa
Netherlands	Max. unweighted SEL_{ss} ($L_{E,\max}$) at 750 m = 159-172 dB re 1 μPa²s, depending on season and number of piles. After 2023: Max. unweighted SEL_{ss} ($L_{E,\max}$) at 750 m = 168 dB re 1 μPa²s
Taiwan	Max. unweighted SEL_{ss} ($L_{E,\max}$) at 750 m = 160 dB re 1 μPa²s
USA	Max. frequency weighted SEL_{cum} exposure per species group (NMFS, 2018)

The results of the questionnaire applied in this project revealed that the industrial partners are currently or in the future active in the coastal waters of Germany, UK, Denmark, Netherlands, Belgium, France, USA Taiwan, Japan and South Korea (see Table 1). Therefore, the sound limits were listed for these countries as far as these could be found by us (Table 4).

All in all, the choice and application of impulse noise thresholds varies among countries and regions. Development of a bubble screen should aim at meeting the strictest regulations to become widely applied. The USA applies TTS/PTS-threshold values, whereas European and Asian countries that follow European countries concerning sound limits, choose more stringent limits that aim to protect against disturbance/avoidance.

The European and Asian limits apply to unweighted broadband SEL, which means that the bubble screen must be effective at the main piling noise frequencies (typically 80-400 Hz). In the USA, the sound exposure calculations for the assessment of the impact of piling noise on marine mammal hearing (TTS/PTS) are based on frequency weighted SEL, which means that bubble screen design can possibly be optimized to the species of interest. For high-frequency cetaceans such as the harbor porpoise bubble screens are more effective, because these generally have maximum reduction at higher frequencies (>250 Hz).

6 Mitigation of impulse noise by bubble curtains

6.1 Realistic noise levels

By filling in the questionnaire, the industrial companies bring information on:

- Typical frequency range and noise level during piling, with and without mitigation
- Construction characteristics
- Hammer type
- Hammer energy
- Pile size (diameter, piled depth), current and future
- For jacket foundations: pre-piling or post-piling
- Applied mitigation measures (NMS/HSD/AdBM, SBBC, DBBC)
- Soil conditions

Realistic sound levels of piling are approximately 170-180 dB unweighted single strike SEL on a distance of 750 m without mitigation. Depending on local rules, these sound levels are reduced with approx. 10-20 dB to a range of 155 and 165dB. The Lp,pk for piling is approx. 20-23dB higher than the SEL. This applies to broadband and single strike. Cumulative sound levels depend on the pile and the concomitant energy profile and the number of strikes as well as the extent of the wind farm in case of a longer period. Table 5 and Figure 2 show some typical piling noise spectra, depending on various characteristics of pile, hammer and environment. More recent data will be collected in WP6A of the Bubbles JIP project.

Table 5 Overview of data from measurements during the piling for Dutch North Sea wind farms (de Jong et al., 2019a)

Project	Gemini			Luchterduinen		PAWP (Q7)	
Pile	U8	Z2	OHVS (jacket)	EL39	EL42	53	OHVS
Pile diameter [m]	7.0	6.6	2.4	5.0	5.0	4.0	4.0
Pile length [m]	66.5	63.4	58.4	68.4	75.9	54.0	54.0
Hammer energy [kJ]	1100	600	600	750	1100	800	800
Water depth at the pile [m]	34.1	30	35	21.5	20.6	21.5	22
Average wind speed [m/s]	8.8	6.6	4	5	9	4-6	4-6
Measurement distance [m]	732	677	921	750	750	891	981

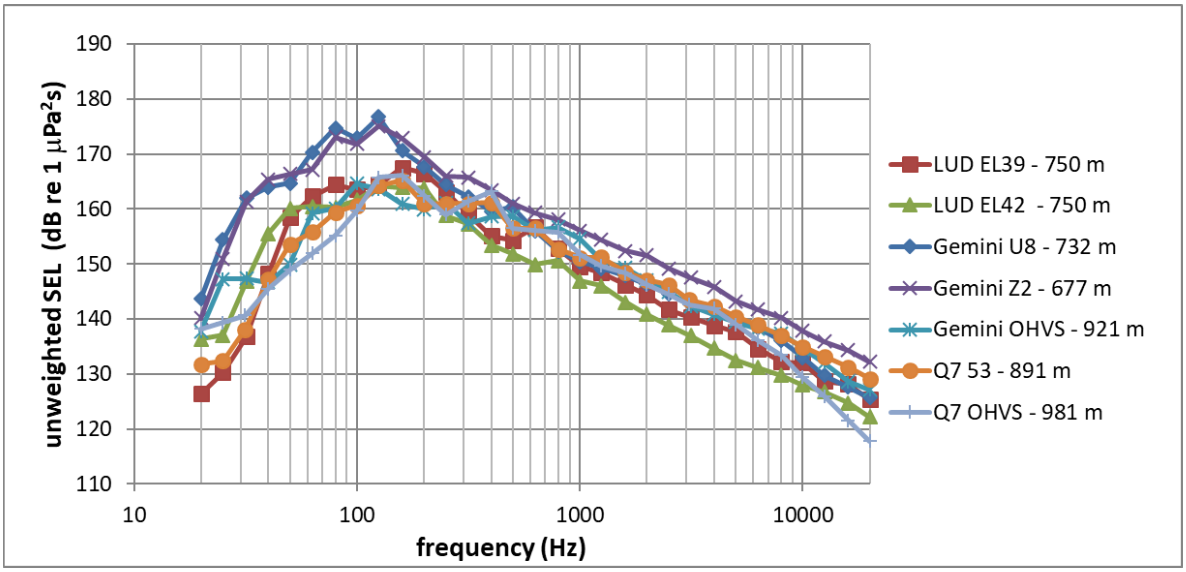

Figure 2 Average one-third octave band spectra of the unweighted single strike sound exposure level for the different North Sea piling projects summarized in Table 5.

6.2 Bubble curtains

There are several factors that limit the effectiveness of state-of-the-art bubble curtains. In this section a concise overview will be given of the current experience with the application of bubble screens to mitigate underwater noise during offshore piling activities.

Dähne et al. (2017) studied the effects of pile driving noise by passive acoustic monitoring and harbour porpoise (*Phocoena phocoena*) echolocation. An acoustic deterrence device (seal scarer) and bubble curtains were used to protect porpoises from hearing loss and attenuate the pile driving noise. Porpoise occurrence decreased during pile driving up to 5h after pile driving and extended out to 12km. Application of a single bubble curtain and two bubble curtains attenuated the noise by 7-10 dB and by 12 dB respectively. Attenuation was most pronounced at frequencies above 1 kHz, where pile driving noise at larger distances was comparable to or lower than ambient noise.

Kastelein et al. (2019) studied the effects of underwater sound from airguns on harbour porpoises by attenuating the noise with the use of bubble curtains. The study was performed in a pool with captive harbour porpoises. A plastic and aluminium screen with encapsulated air bubbles was placed between the airgun and the harbour porpoises. The bubble screen reduced the energy of broadband sounds above 250 Hz, but the unweighted broadband single shot sound exposure level was only reduced by 3 dB. However, the bubble screen was very effective in reducing the behavioural responses of the porpoises to the airgun sounds. Furthermore, this study provides support for the hypothesis that frequency content matters in the assessment of responsiveness of harbour porpoises to impulsive broadband sounds.

Tougaard & Mikaelsen (2017) give an overview on how to effectively mitigate the effects of noise produced by pile driving for Taiwanese white dolphins. The use of bubble curtains is proposed as the best mitigation measure following the European noise level regulations and due to the lack of sufficient information about hearing values of Taiwanese white dolphins, the threshold values of harbour porpoises are applied.

Figure 3 (from Bellmann et al., 2020) shows the spectrum of the average noise reduction achieved with current noise mitigation systems (including bubble screens). This shows that current bubble screens provide their maximum reduction at frequencies (>250 Hz), largely above the dominant frequency range for unmitigated impact piling noise (80-400 Hz). The mismatch between the piling noise and bubble curtain mitigation spectra means that bubble curtains are relatively inefficient in reducing broadband sound levels caused by pile driving: the peak reduction is in a part of the noise spectrum where comparatively little energy is produced.

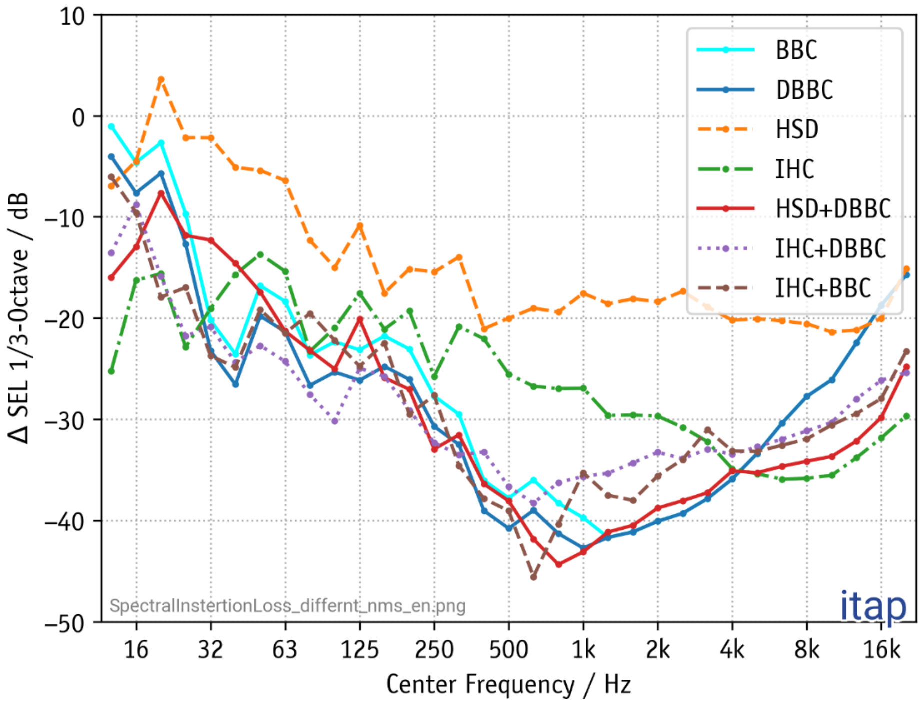

Figure 3 Noise reduction (insertion loss) of different Noise Abatement Systems (from Bellmann et al., 2020): IHC-Noise Mitigation Screen (NMS8000), Hydro Sound Damper (HSD) and optimized single/double Big Bubble Curtain (BBC/DBBC), averaged over all applications within the German EEZ of the North Sea.

It should be noted that:
- the influence of bubble curtain characteristics (diameter of bubble curtain, diameter of bubbles, density of bubbles) on the noise reduction is insufficiently known;
- the observed decrease in noise reduction with increasing frequency above 1 kHz is not understood;
- Influence of environmental characteristics (water depth, currents, waves and sediment properties) on the noise reduction is insufficiently known;
- the subsoil is also responsible to transfer energy/noise but further investigations of the role of the subsoil is outside the scope of the research in the Bubbles JIP project.

6.3 Construction characteristics and environmental conditions

Piling sound generation and propagation depend on many factors. For modelling, de Jong et al. (2019b) use the following factors:
- type of hammer, mass of the hammer and hammer strike energy
- anvil mass and contact stiffness
- diameter, wall thickness and material of the pile
- length of the pile in the water and in the bed
- mitigation measure (bubble screen, mantle, etc.)
- water depth (bathymetry) around the pile
- seabed properties around the pile (density, sound velocity and absorption)
- wind speed/wave height.

The outcome of the questionnaire (chapter 2) provides the major part of the required information on the relevant constructions characteristics and environmental conditions and the delimitation that can be applied in other WPs of the Bubbles JIP project.

7 Conclusions and recommendations

The Bubbles JIP project brings together the relevant engineering disciplines (acoustics, hydrodynamics and process control) for understanding and optimizing the efficiency of bubble curtains for reducing the underwater sound (form) for offshore piling projects.

It is expected that meeting/complying with the noise limits for future projects (at increasing water depth and pile size) cannot be guaranteed with the current generation bubble curtains, and therefore contractors require:

1. More effective bubble curtains (a practical bubble curtain system solution at minimum cost and emissions);
2. A procedure (or models) for reliable estimation of the achievable noise levels (broadband SELss at 750 m from the pile) with optimized bubble curtain.

For both objectives there is a need for better understanding of the parameters that determine the effectiveness of bubble curtains:

- In general terms, a bubble curtain reduces underwater sound because:
  - Underwater sound reflects at the transitions between 'water' and 'bubbly water'. The reduction in sound increases if the air volume fraction in the bubbly water layer (the 'curtain') is higher but has to be further validated in the Bubbles JIP because it might be the case that after a certain point a plateau is reached This volume fraction is influenced by the volume flow of the air (and the rise velocity of the bubbles) as well as by the cross-sectional shape (thickness) of the bubble curtain. Hence, the sound reduction varies over the water depth and possibly also over the circumferential length of the curtain.
  - Underwater sound is absorbed by resonating bubbles. Hence, bubble curtains produce additional sound reduction at bubble resonances frequencies.

- The parameter dependencies are not well known. There is limited experience with modelling of the full system (from compressor and hose design to sound reduction) and even less model validation. Hence, predictability and optimization are difficult. The Bubbles JIP work packages 2 and 5 are aimed at further model development and validation.

- Currently, noise limits are specified in terms of the broadband SELss at 750 m from the pile. For some marine mammal species (e.g. harbor porpoises, that have high frequency hearing) this may not be the most appropriate metric. This may change in the future. US regulators have already incorporated frequency weighted metrics in their acoustic impact assessment. Where possible, frequency dependence must be considered in the modelling.

- There is an offset between the energy spectra of piling noise, with peak energies between ~80-400Hz and the observed reduction spectra of current industry-practice bubble curtains, with peak mitigation around >500Hz. A shift of the mitigation spectrum of bubble curtains towards lower frequencies would be more efficient in reducing the broadband sound levels; this may be possible e.g. by producing larger bubbles with a lower resonance frequency. This principle is applied in the design of systems such as HSD (encapsulated bubbles) and AdBm (Helmholtz resonators), which are based on low-frequency resonators. Compared to bubble curtains, these systems have a limited effectiveness at higher frequencies.

- The effectivity of bubble curtains depends on local environmental parameters:
  - Water depth and currents.
  - Sea floor properties: 'the harder the sediment, the more effective the bubble curtain (but the unmitigated piling noise levels are also higher)', and the distance between pile and bubble curtain strongly affects the amount of 'leakage' of sound due to sound propagation through the sediment.

- The operational effort and environmental footprint involved with large bubble curtains is significant. Increasing the total air flow over what is used today, is generally not feasible without mobilizing additional vessels and a considerably larger compressor spread (with its additional emissions).

- Current generation bubble curtains provide a limited control of parameters:
  - Pressure and volume flow of the air (number and capacity of compressors, which are capped by operational restrictions).
  - Geometry of the hose (length, distance to the pile, shape).

- For optimization of the (frequency dependent) noise reduction, the bubble size distribution in the curtain may be optimized by adapting the nozzle hose design parameters (e.g. diameter, nozzle shape and size, spacing), hose geometry, air flow and air pressure, but regulators do not always allow modifications to the current practice unless convincing evidence can be produced.

- The model development (WP2, WP5) should aim at including the environmental parameters as boundary condition for selecting the bubble curtain design parameters.

- The model validation experiments (WP4, WP6) should aim at providing the data for validating the modelled parameter dependencies.

- An overview of the parameter space for the further development of bubble screen solutions is provided in Table 4 (*Summary of piling sound limits)* in chapter 5 (*Regulations, rules and criteria*) of this WP1 report.

8 Quality Assurance

Wageningen Marine Research utilises an ISO 9001:2015 certified quality management system. The organisation has been certified since 27 February 2001. The certification was issued by DNV.

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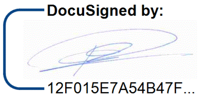
Justification

Report C021/23
Project Number: 4315100148

The scientific quality of this report has been peer reviewed by a colleague scientist and a member of the Management Team of Wageningen Marine Research

Approved: Dr. Robbert Jak
Researcher

Signature:



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MT Member

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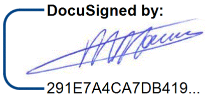

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Annex 1 Audiograms of marine mammals

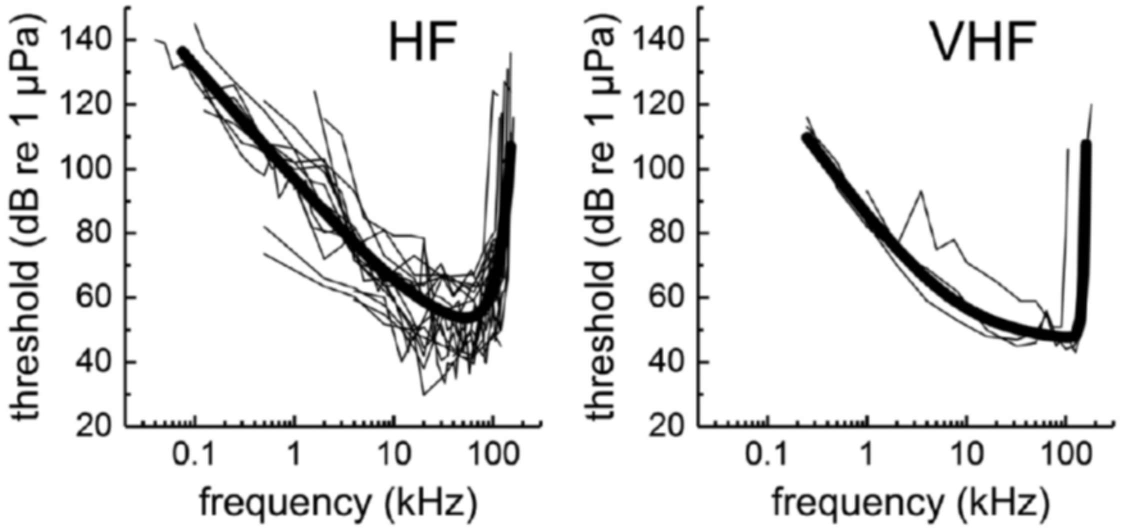

Figure 4 Estimated group audiograms for high-frequency (HF) and very high-frequency (VHF) cetaceans. Source: Southall et al. (2019).

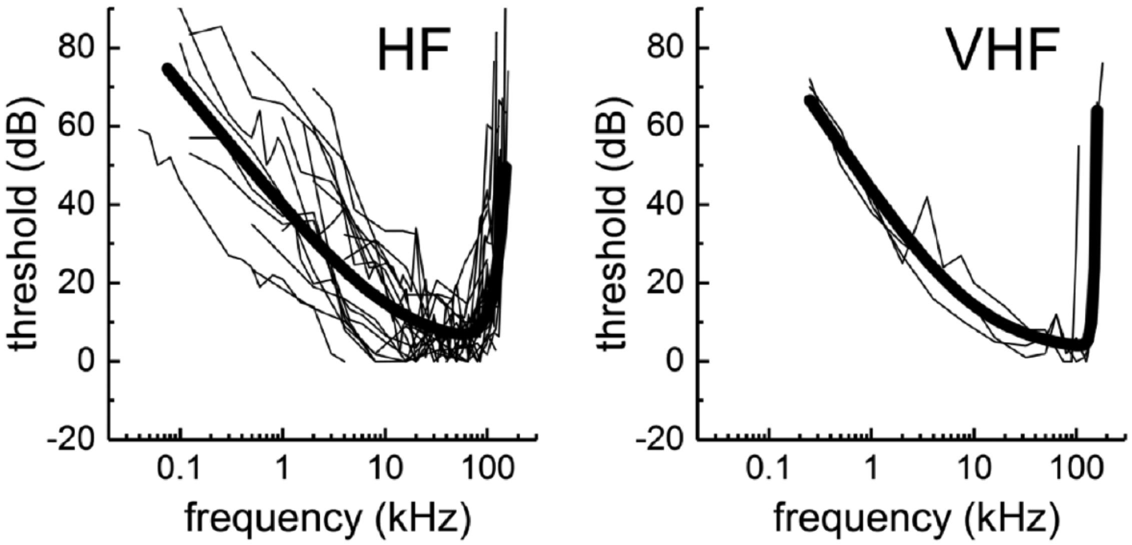

Figure 5 Normalized group audiograms for high-frequency (HF) and very high-frequency (VHF) cetaceans. Source: Southall et al. (2019).

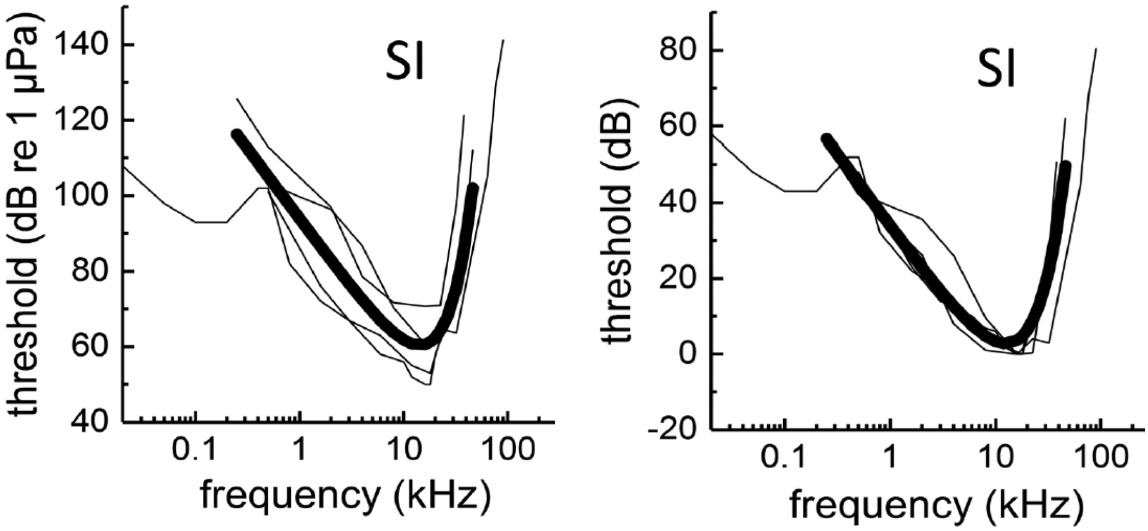

Figure 6 Estimated group audiograms (left) and normalized group audiograms (right) for sirenians (SI). Source: Southall et al. (2019).

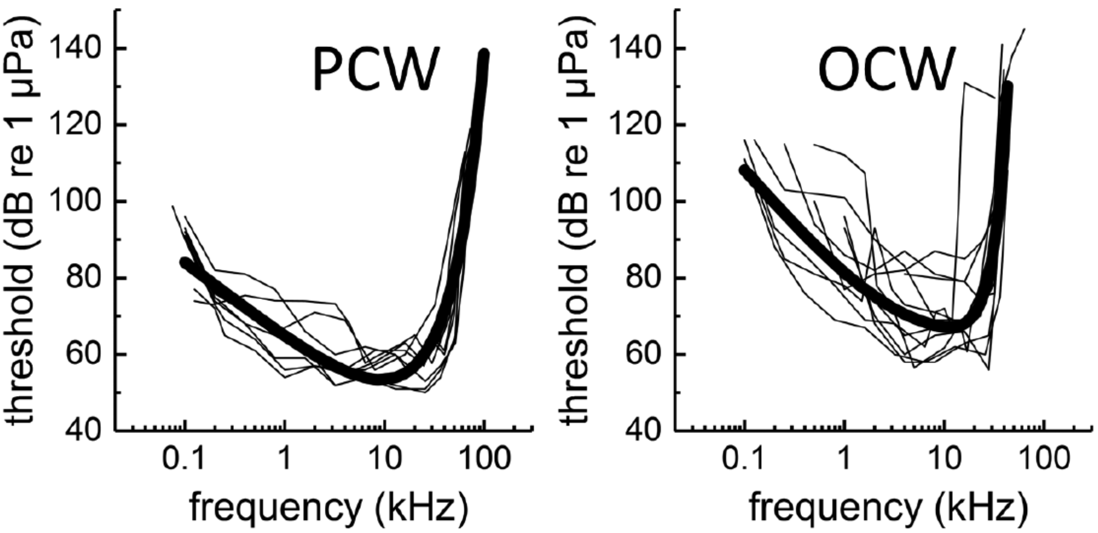

Figure 7 Estimated group audiograms for phocid carnivores in water (PCW, left) and other marine carnivores in water (OCW, right). Source: Southall et al. (2019).

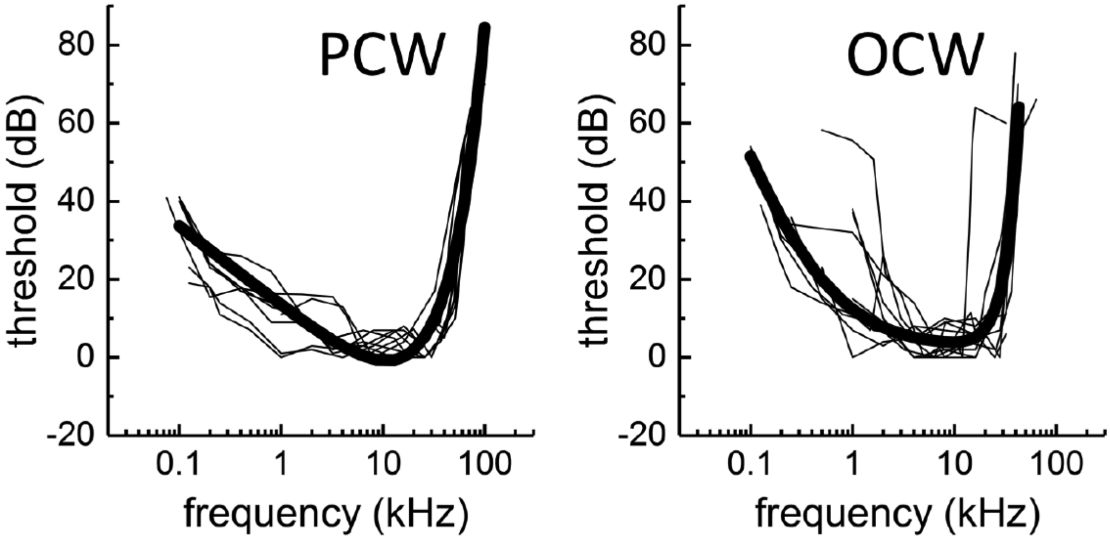

Figure 8 Normalized group audiograms for phocid carnivores in water (PCW, left) and other marine carnivores in water (OCW, right). Source: Southall et al. (2019).

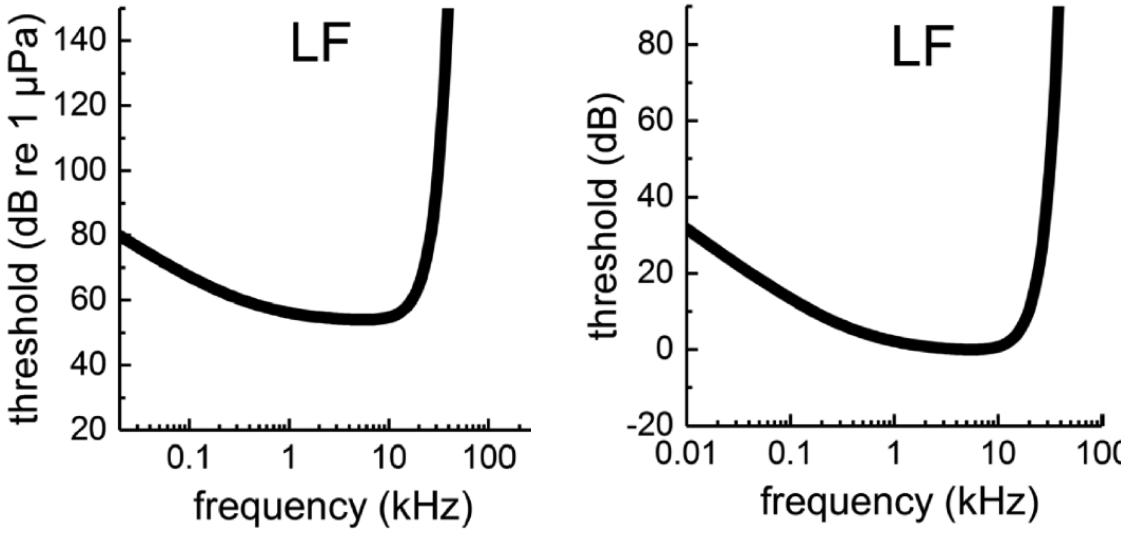

Figure 9 Estimated group audiograms (left) and normalized group audiograms (right) for low-frequency (LF) cetaceans. Source: Southall et al. (2019).

Annex 2 Exposure functions of marine mammals

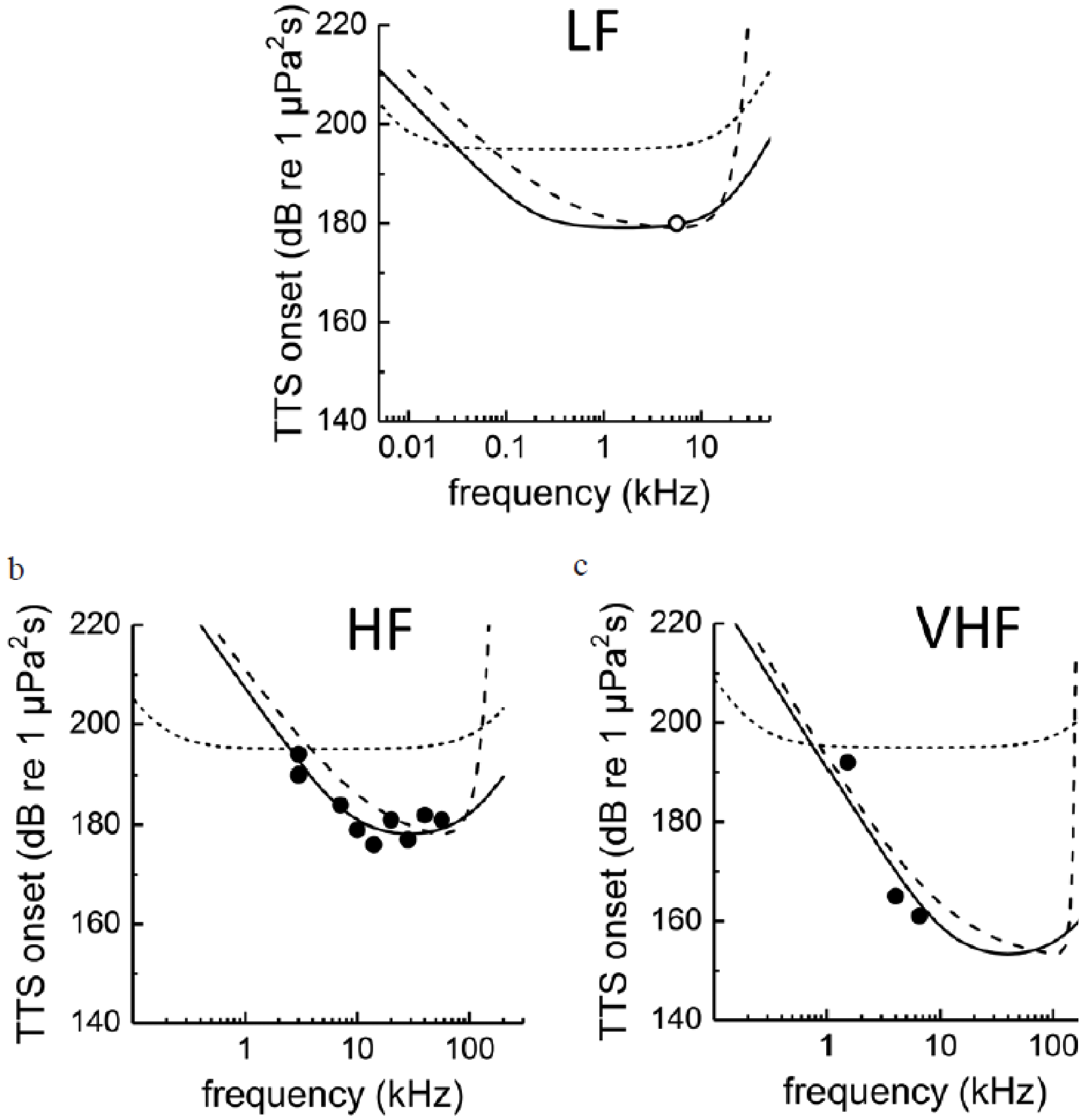

Figure 10 Exposure curves for low-frequency (LF), high-frequency (HF) and very high-frequency (VHF) cetaceans. Source: Southall et al. (2019).
*Exposure functions (solid lines) for LF (top), HF (bottom left), and VHF (bottom right) cetaceans generated with Equation (3) using parameters from Table 6. Open symbol for LF cetaceans indicates the estimated TTS onset at **f0** based on TTS data from other groups given that no direct empirical data exist for any LF species. Filled symbols indicate empirical onset TTS exposure data used to determine exposure functions for HF and VHF cetaceans. Normalized estimated group audiograms (dashed lines) are shown for comparison with a minimum value identical to that of the associated exposure functions. Estimated exposure functions derived from M-weighting filters each respective group with a minimum value set at the estimated TTS-onset value (dotted lines) are also shown for comparison (derived from Southall et al., 2007).*

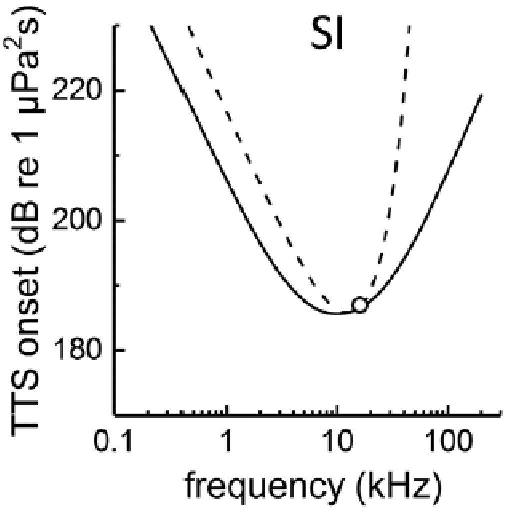

Figure 11 Exposure function (solid line) for sirenians generated with Equation (3) using parameters given in Table 6. The normalized SI estimated group audiogram (dashed line) is shown for comparison with a minimum value identical to that of the exposure function. The open symbol indicates the estimated TTS onset given that no TTS data of any kind exist for sirenians. The SI normalized estimated group audiogram (dashed line) is shown for comparison with a minimum value identical to that of the associated exposure functions.

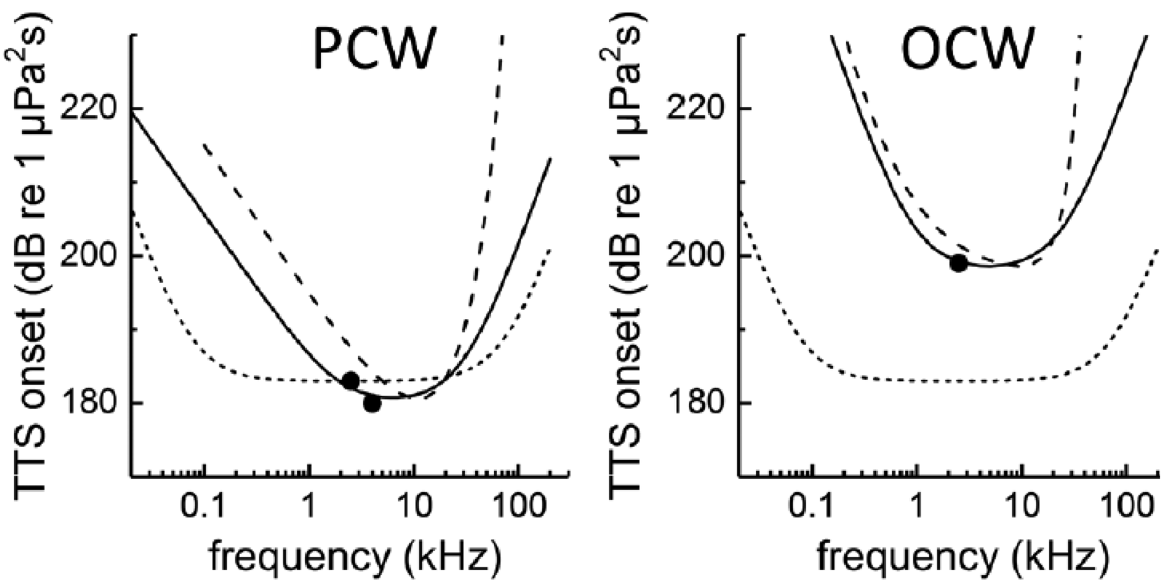

Figure 12 Exposure functions (solid lines) for marine carnivores in water (PCW and OCW) generated with Equation (3) using parameters given in Table 6. Filled symbols indicate empirical onset TTS exposure data used to determine the exposure function. Normalized estimated group audiograms for PCW and OCW (dashed lines) are shown for comparison with a minimum value identical to that of the associated exposure functions. Estimated exposure functions derived from M-weighting filters for pinnipeds in water with a minimum value set at the estimated TTS-onset value (dotted lines) are also shown for comparison on both plots; this was a single function for all pinnipeds in Southall et al. (2007).

Annex 3 Questionnaire

Questionnaire Bubbles JIP WP1: Defining the starting conditions

This questionnaire is sent to the contact persons of all project partners (Boskalis, HMC, IHC, SHL, Van Oord, Marin, TNO, TUD) (see *Table 7*) in order to collect their experience and view on the definition of the starting conditions of the Bubbles JIP project. It is essential that the industrial company partners answer the questions, but the research institution partners are also invited to respond on the topics of their interest and experience.

The questionnaire is sent to all contact persons on the Bubbles JIP contact persons list (see attachment) and it is preferred to receive the attuned response of each company via the main contact person.

This questionnaire is intended to clarify which wind turbine piling characteristics and environmental conditions (for current and future piling projects) should be included in this project based on the experience and future plans of the company. Therefore, please provide information on the topics by filling in the table (*Table 6*).

Table 6 Questionnaire format sent to the respondents

Questions/Topics	**Answers**
Construction characteristics	
Hammer type	
Hammer energy	
Pile size (diameter, piled depth), current and future	
For jacket foundations: pre-piling or post-piling	
Applied mitigation measures (NMS/HSD/AdBM, SBBC, DBBC)	
Typical frequency range and noise level during piling, with and without mitigation	
Abiotic environmental conditions	
Water depths	
Mean current speed	
Sea floor characteristics (sediment types, slope)	
Distances to coast	
Regional seas and involved countries (for licensing)	
Experience and expectations	
Current experience with the application of bubble screens. What are the limiting factors?	
Expected limitations for future effective mitigation by bubble screens	

Name: ...
Company
Date:

After filling in, please return the form to Ruud Jongbloed (Wageningen Marine Research) by mail: ruud.jongbloed@wur.nl., preferably as soon as possible, but before August 15, 2020.

Table 7 List of respondents contacted for the questionnaire

Name of industrial company/ research institution	Contact person	Date of response
IHC IQIO	Jonathan Stolk	22-07-2020
Seaway 7	Louisa Braakenburg	23-07-2020
Boskalis	A. Baas & R. van der Wal	03-09-2020
Heerema Marine Contractors	Marco Huisman	21-07-2020
Van Oord	Tasos Stampoultzoglou	28-08-2020
TNO	Christ de Jong	11-08-2020
Delft University of Technology	Apostolos Tsouvalas	27-08-2020
MARIN	Linda Kemp	25-08-2020

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- Haringkade 1, 1976 CP IJmuiden

With knowledge, independent scientific research and advice, **Wageningen Marine Research** substantially contributes to more sustainable and more careful management, use and protection of natural riches in marine, coastal and freshwater areas.

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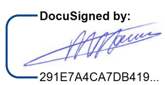

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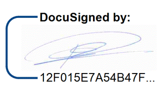

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