Revised Danish Guidelines for Underwater Noise from Installation of Impact or Vibratory Driven Piles

René Smidt Lützen, Søren Keller, and Jakob Tougaard

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R. S. Lützen (✉)
Vysus Denmark, Copenhagen, Denmark
e-mail: rene.smidtluetzen@vysusgroup.com

S. Keller
Danish Energy Agency, Copenhagen, Denmark
e-mail: ske@ens.dk

J. Tougaard
Aarhus University, Department of Ecoscience, Roskilde, Denmark
e-mail: jat@ecos.au.dk

A. N. Popper et al. (eds.), *The Effects of Noise on Aquatic Life*,
https://doi.org/10.1007/978-3-031-10417-6_96-1

Abstract

Since 2016, underwater noise from the construction of offshore wind in Danish waters has been addressed by guidelines from the Danish Energy Agency. These guidelines were updated in 2022 and specify technical methods for performing numerical prognosis and on-site measurements. Acoustic criteria are stated for compliance, including Permanent Threshold Shift (PTS) and behavioral impact. These criteria are based on auditory frequency-weighted levels.

Impact pile driving and vibratory pile driving installation techniques are addressed, with separate methods for modeling and measurements. Concession holder is required to carry out a prognosis to estimate the environmental impact using the given sound source and propagation properties and calculate the acoustic metrics experienced by a receptor (marine mammal) while it is fleeing away from the noise source. The prognosis must be carried out for two to three scenarios, on fully numerical or semi-empirical basis: reference case, planned construction case, and if relevant a specific case including acoustic deterrent device (ADD).

For comparison with measurements during pile installation, the prognosis is required to provide predictions for certain acoustic metrics that are suited for direct measurements.

On-site measurement of underwater sound during installation is required for two purposes: verification of the propagation model used for the prognosis and demonstration of compliance with the acoustic criteria.

Keywords

Acoustic criteria · Pile driving · Acoustic deterrent device · Noise prognosis · Frequency weighting · PTS · Behavioral response · Marine mammals

Introduction

Underwater noise from percussive (hereafter "impact") pile driving is recognized as having a substantial impact on marine mammals. For this reason, the Danish 2016 Guidelines for underwater noise from installation of impact-driven piles were made (Danish Energy Agency 2016). In that first version of the guidelines, only impact in the form of permanent injury to marine mammal hearing was addressed. The reason for this was that at the time of writing, the empirical evidence of other forms of impact was found to be insufficient to establish regulatory thresholds. However, as new empirical evidence became available, a revision of the guidelines became pertinent. The relevant new material was extracted in a series of technical reviews (Tougaard 2021a, b; Tougaard et al. 2021, 2022) that served as background for the revised guidelines. The most important changes from the 2016 guidelines are inclusion of criteria for behavioral disturbance of marine mammals and introduction of auditory frequency weighting for different functional hearing groups. Furthermore, the guidelines now specify criteria and procedures for the use of acoustic deterrent devices (ADDs), adapted procedures for impact and vibratory driving, and procedures for calculation of distance-to-threshold in assessments.

The guidelines relate to a set of standard conditions, which are usually included in the construction permit for Danish offshore windfarms. Standard conditions, the guideline document itself, and the background reports are available from the Danish Energy Agency website, www.ens.dk. This text presents an overview of the guidelines. For correct application of the guidelines, the reader must consult the guideline document itself (Danish Energy Agency 2022).

Regulations for Underwater Noise

Over that past several decades, a steady increase in anthropogenic underwater noise has been observed in the seas, e.g., McDonald et al. (2006). The associated risk of a negative impact on a broad range of marine life has motivated regulatory initiatives worldwide. Regulation for underwater noise is an evolving topic and is handled differently among regulators. A few examples of international (European) regulatory frameworks, according to (Lucke 2020), include:

- EU Habitats Directive for conservation of natural habitats and of wild flora and fauna (European Commission 1992). Does not explicitly mention underwater noise but regulates activities and projects that can potentially injure and/or disturb animals, in this context in particular marine mammals.
- Marine Strategy Framework Directive (MSFD) (European Commission 2008). European legislation that considers a multitude of anthropogenic "stressors" and cumulative effects. Specifically addresses underwater noise and requires that EU member states establish thresholds for good environmental status with respect to underwater noise that can impact marine organisms negatively (European Commission 2017).
- The Baltic Marine Environment Protection Commission (HELCOM) has adopted a Regional Action Plan for underwater noise (Helcom 2021), which specifies actions to reduce impact from, among other sources, impact pile driving.

In Danish waters, the legal framework for offshore wind farms is the Act on Promotion of Renewable Energy (Danish Government 2008). On the technical side of regulation, significant variation exists among countries and frameworks. A multitude of acoustic metrics are referred to, and in some cases, auditory frequency weighting of metrics is mandated. In recent years, international standardization on this topic is gradually coming into shape (International Organization for Standardization 2017a,b), but the application differs greatly from one regulator to another. For regulation of underwater noise in the context of offshore wind farms, a few country-specific examples are included to illustrate the diversity:

USA

The seminal review by Southall et al. (2007) introduced the onset of permanent hearing loss (PTS) as a precautionary criterion for acoustic injury in marine mammals. For this purpose, marine mammals were divided into functional auditory groups, with different sets of criteria for impulsive and non-impulsive types of noise. For each type of noise and each functional hearing group, a double criterion was established, such that for each functional hearing group two levels were specified, and none of which are allowed to be exceeded. The first criterion is a cumulative sound exposure level (abbreviated as SEL_{cum}), frequency weighted with an auditory frequency weighting curve specific for the functional hearing group, and the second criterion is an unweighted zero-to-peak sound pressure level. These guidelines were updated recently (National Marine Fisheries Service 2018) (Southall et al. 2019).

Germany

For more than a decade, German Federal Maritime and Hydrographic Agency (BSH) have imposed a dual-metric criterion for pile driving (BSH 2011), aligned with recommendations from the Environmental Protection Agency (German Federal Ministry for the Environment and Nuclear Safety 2013) and specifically targeted protection of harbor porpoises (*Phocoena phocoena*). Evaluation is at 750 m range from the piling, in terms of the single-strike sound exposure level and peak sound pressure level without frequency weighting. For measurements during construction, percentile statistics are required, calculated from measurements on a large number of individual pile driving strikes. The single-strike sound exposure level (unweighted) is not to exceed 160 dB re 1 μPa^2 s and peak-to-peak pressure not to exceed 190 dB re 1 μPa.

Belgium

In Belgium, the underwater noise from piling must comply with a zero-to-peak sound pressure level threshold (185 dB re 1 μPa) at a range of 750 m (Rumes, 2016). This criterion is without frequency weighting.

Denmark

In 2016 the Danish Energy Agency published its first version of the guidelines for underwater noise, addressing offshore pile installation (Danish Energy Agency 2016). The main metric considered was the sound exposure level, cumulated over all pile strikes within piling of a single foundation. Corresponding threshold values were not stated directly in the guidelines, as the intention was for these to be specified in the conditions of the construction permit. No frequency weighting was required in the 2016 guidelines.

As a novel concept in a regulatory context, the first version of the Danish guidelines introduced a numerical framework for calculating the SEL_{cum} of a moving receiver (animal fleeing from the noise source at a constant speed).

In the current version (Danish Energy Agency 2022), the concept of the constant speed-fleeing animal has been kept, and several new features have been implemented. The most significant being frequency weighting according to species group-specific weighting functions with associated group-specific acoustic criteria.

Scope of the Revised Guideline

For installation of offshore wind turbine foundations, the requirements of the Danish Energy Agency for minimizing the environmental impact from underwater noise form part of the conditions of the construction permit. On this background, the concession holder is obliged to demonstrate plans for how to comply with these requirements. This means the concession holder must prepare a prognosis for underwater noise generated during construction. This prognosis must then be used as the starting point for an environmental impact assessment addressing the potential impact of underwater noise on marine mammals and selection of adequate mitigation measures. In addition, it is mandatory for the concession holder to conduct a verification measurement program. The corresponding methodologies, requirements, and criteria are described in the 45-page guideline and presented in a summarized version in this chapter.

The revised version of the guidelines presented here covers both impact pile driving and vibratory pile driving. While other installation techniques exist, these are not within the scope. Similarly, noise from operational wind turbines and service vessels is also not covered. The primary application of the guidelines is therefore installation of large-diameter monopiles and multi-pile foundations such as jackets and tripods. As an additional new aspect, the guidelines present procedures for permitting and impact assessment of acoustic deterrent devices (ADDs) when deployed as part of the mitigation strategy.

The core of the guidelines is a criterion for the onset of Permanent Threshold Shift (PTS) taken as a precautionary proxy for injury, in line with recommendations of Southall et al. (2007, 2019) and following the same grouping of species according to hearing abilities. Only species relevant in the context of Danish waters are considered, thus covering harbor porpoise (VHF cetaceans), small delphinids (HF cetaceans), minke whale (*Balaenoptea acutorostrata*, LF cetaceans), and phocid seals in water (PCW). In terms of metrics, these criteria are stated as SEL_{cum} (sound exposure level) cumulated over all the impulsive sounds received by the animals during piling of one foundation, weighted by the appropriate auditory frequency weighting functions (Southall et al., 2019, Tougaard et al., 2022).

In addition, the guidelines provide threshold values for the evaluation of behavioral reactions to underwater noise in harbor porpoises. These thresholds are expressed as root-mean-squared sound pressure levels over 125 ms ($SPL_{125\ ms}$), weighted by the appropriate auditory frequency weighting functions (Tougaard 2021a).

During pile installation, measurements must be taken with the purpose of comparison with the prognosis. To that end, and to enable direct comparison, the prognosis must provide predicted values for the following metrics at distances 750 m, 1500 m, and 3000 m:

- Single-strike sound exposure level (SEL_{ss}) and single-strike root-mean-squared sound pressure levels ($SPL_{125\ ms}$) for impact driving, unweighted and frequency weighted.
- Sound pressure level (SPL) for vibratory driving, unweighted and frequency weighted.

Currently, behavioral impacts are only addressed in the guidelines to the extent that indicative frequency-weighted thresholds for onset of behavioral reactions (fleeing) are provided. No hard limit to the spatio-temporal extent of the disturbance is provided. Instead, the assessment of the likely impact of the disturbance on the local and regional populations of animals is left to the environmental impact assessment. Temporary habitat loss is thus not addressed in detail by the guideline. However, for example, the reader may refer to Tougaard (2021a). It is, however, expected that this topic becomes further developed in future revisions.

The concession holder must carry out an on-site validation of the model, regardless of how the acoustic model was established. Similarly, it is a requirement to perform on-site measurements and demonstrate that the acoustic criteria are fulfilled.

New Knowledge Since the First Guideline Version

The empirical foundation for regulation of underwater noise expands rapidly these years, which means that guidelines should always be considered interim and should be revised whenever there is significant new information about the impact of noise, biology of the animals, or change in the overarching legislation. Since the previous guidelines (2016) were established, two important developments occurred, resulting in significantly improved knowledge about prediction of the impact and means for mitigation. These developments were revised recommendations for frequency weighting (Southall et al., 2019) and the availability of efficient noise abatement technologies, e.g., Bellmann et al. (2020).

Frequency Weighting

The concept of auditory frequency weighting of noise in assessment of its potential to cause auditory damage is well-established for humans (see Houser et al. (2017) for a review) and was introduced in regulation of underwater noise impact on marine mammals by Southall et al. (2007). The proposed M-weighting curves were very wideband, which meant that the difference between regulation based on unweighted and M-weighted levels in regulation of pile driving noise was very small (Tougaard and Dähne 2017). However, new empirical data on temporary threshold shifts (TTS) produced after the review by Southall et al. (2007) challenged this, as data were more consistent with sharper weighting functions, resembling inverted audiograms (Tougaard et al. 2015). Subsequently, this led to a revision of the weighting functions (Southall et al. 2019). Thus, the revised Danish guidelines now follow recommendations of Southall et al. (2019), which means that the cumulative sound exposure level (SEL_{cum}), weighted with the species-appropriate auditory weighting function, cannot exceed levels that are considered to represent a significantly elevated risk of inducing permanent hearing impairment (Permanent Threshold Shift, PTS). For pile driving noise, classified according to Southall et al. (2019) as an impulsive sound, the species group-specific levels of relevance in Danish waters are given in Table 1. The associated auditory frequency weighting curves are shown in Fig. 1.

Table 1 Species of relevance in Danish waters, with associated auditory frequency weighting functions and limit values for cumulative sound exposure level SEL_{cum}

Species group	Weighting function	SEL_{cum} limit (dB re 1 μPa^2 s)
Phocid seals (harbor seal, grey seal)	PCW	185
Mysticetes	LF	183
Odontocetes, except porpoises	HF	185
Harbor porpoise	VHF	155

PCW, phocid carnivores; *LF*, low-frequency cetaceans; *HF*, high-frequency cetaceans; *VHF*, very-high-frequency cetaceans

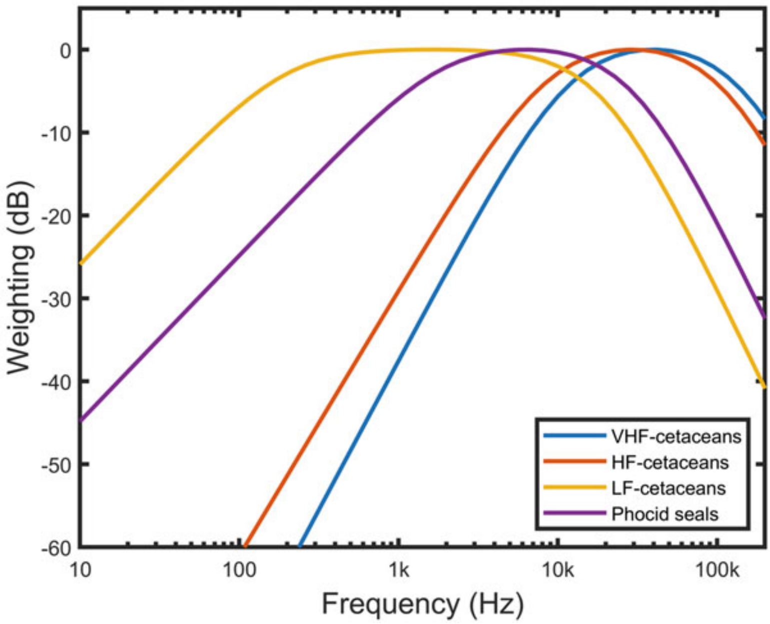

Fig. 1 Frequency weighting functions proposed by Southall et al. (2019) and Tougaard (2021b) for auditory groups relevant to Danish waters

Southall et al. (2019) operates with a dual criterion, one based on the cumulative sound exposure level, frequency weighted, and one on the unweighted peak pressure. As the SEL_{cum} criterion is expected always to be exceeded before the peak pressure criterion for pile driving noise, only the SEL_{cum} criterion is applied in the guidelines. The guidelines may be extended to other types of impulsive sources, such as seismic air guns, but not to all types. Most important exception is explosions, where the peak pressure is likely to be the better predictor of the risk of injury.

Disturbance of Behavior

New in the guidelines compared to the previous version is that the impact from behavioral disturbance of marine mammals must now be included in an assessment, and a threshold for evaluating disturbance is provided. This threshold, valid for harbor porpoises, is expressed as an auditory frequency-weighted sound pressure level, calculated as a root-mean-squared (RMS) average over 125 ms, corresponding to the integration time of the mammalian auditory system (Tougaard et al. 2015, Tougaard 2021b). Recent empirical data supports the notion that frequency-weighted sound pressure levels are better predictors of behavioral response to pile driving noise than are unweighted levels (Kastelein et al. 2022). Based on a review of experimental data (Tougaard 2021b), including both experiments on animals in captivity and studies of wild porpoises' reactions to full-scale pile driving, a threshold for behavioral reactions equal to 103 dB re 1 μPa, VHF-weighted, is provided.

Metrics and Terms in the Revised Guideline

Metrics used in the guideline follow the definitions given in ISO 18405 (International Organization for Standardization 2017a) and ISO 18406 (International Organization for Standardization 2017b). A few additional metrics and terms are:

Max Over Depth Across Water Column

For a fixed range step r_i, and considering the entire water column, the maximum metric value is determined, i.e., max over depth (MOD). With j being the vertical grid-point index, MOD of a given metric L is:

$$L_{MOD}(r_i) = \max_j L_j(r_i)$$

Here, all values of j inside the water column are considered.

Distance to Threshold

Distance to threshold is the largest expected distance from the source where the received level of noise equals the threshold (for onset of PTS or onset of behavioral reactions, whichever relevant). This distance is most often evaluated from a max-over-depth parameter. As such, the distance to threshold (DTT) is used for evaluating the range-dependent variation based on a given acoustic threshold value.

It is worth noting that the sound field in a shallow-water acoustic environment usually decays with distance in a non-monotonous manner. On that background, the numerical evaluation must be implemented carefully to avoid the risk of identifying local features as the global DTT of the transect.

Exceedance Level

For an acoustic-level metric L_x, it is common to define an exceedance level in dB. Applying statistics to L_x, the percentage x is the level which during the observation period is exceeded x% of the time. One common observation period is the piling sequence. Taking as an example L_{90}, this refers to the metric's level that is statistically exceeded 90% of the time. Analogously, L_{50} corresponds to the statistic median and indicates the level that is exceeded 50% of the time.

Acoustic Deterrent Device (ADD)

An acoustic deterrent device (ADD) is a technical device designed with the purpose of emitting an acoustic signal that is unpleasant for the target species. The intention is that the ADD's signal causes any target animals to leave the nearby area as a non-lethal, behavioral response. Historically, ADDs were developed for fisheries and the aquaculture industry for deterring marine mammals, thereby reducing depredation and damage to fishing gear and net pens. Over time, its use spreads to other offshore industries including offshore wind and UXO (UneXploded Ordnance) removal and now includes devices known as "seal scrammers" and "pingers." Deployment of ADDs in this context is then as a mitigation device, with the intention of deterring animals out to safe distances before the onset of the main, potentially harmful noise source. An overview is given in McGarry et al. (2020).

In the context of offshore piling, an ADD serves as a marine mammal mitigation technique. In the ideal case, the ADD deters animals away from the potential injury zone. However, thereby the ADD creates an additional disturbance, on top of the disturbance caused by the pile driving itself. If the ADD is too powerful, the disturbance caused by the ADD may exceed the disturbance from the pile driving itself (Dähne et al. 2017), thereby jeopardizing the very mitigation purpose of the ADD.

In the revised guidelines, it is now a general requirement to use an ADD during the construction activity. This applies to any single foundation, with the only exception being cases that are relatively low noise. The ADD is a significant underwater source of noise itself. In consequence, it is required to assess its acoustic impact. The revised guidelines include a procedure for this specific purpose. The aim is to assure that the distance to threshold for disturbance for the ADD does not exceed the distance to threshold for the pile driving itself, assuring that the ADD does not cause disturbance over a wider area than the pile driving itself. Furthermore, the revised guidelines now require that the ADD is activated at least 15 min prior to start-up of the pile installation activity. If the installation stops for more than 2.5 h continuously, it must not start again before the ADD has been active for another 15 min. This procedure is in line with suggestions presented in Thompson et al. (2020).

Prognosis Overview

Figure 2 shows a flowchart representation of the sequence behind the required prognosis scenarios. The reader is referred to the guideline document for details, but a few features are highlighted in the following.

Overall, the prognosis is intended for estimating the environmental impact resulting from a given sound source and propagation properties. This is done by calculating the acoustic metrics experienced by a marine mammal receptor. The prognosis must be carried out for two to three scenarios, on a fully numerical or semi-empirical basis.

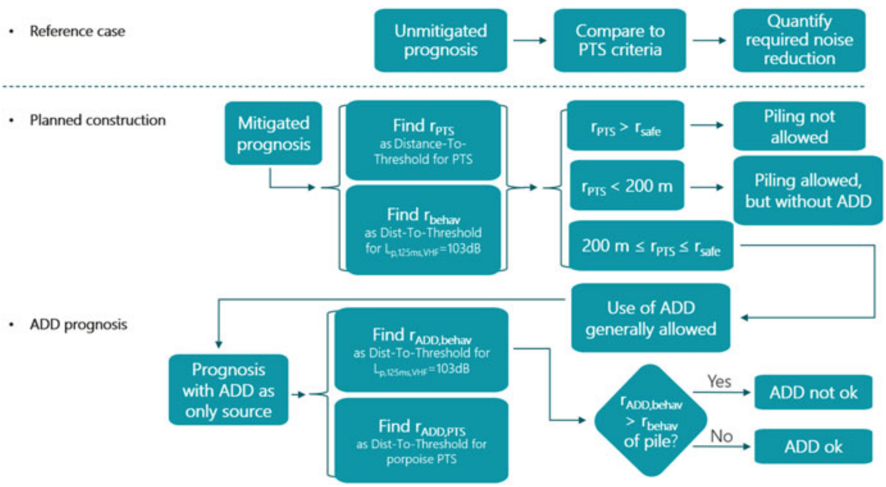

Fig. 2 Prognosis flowchart. Please refer to the guideline document for full details

Reference Case

This is a worst-case scenario, without noise abatement techniques and without ADD. As such, it provides a standardized setup that allows regulators to track technology improvement across projects. In addition, it represents a worst-case indication of what might happen in case of a malfunctioning noise abatement systems. An example would be bubble-curtain compressor failure.

Planned Construction Case

In this scenario the prognosis is based on the installation machinery (e.g., hammer) and noise mitigation techniques (if any, e.g., bubble curtain) intended for the construction. It also assumes the use of an ADD prior to the installation (if relevant, see comments below), resulting in a certain minimum displacement of any nearby animals. This distance is called r_{safe} and must be provided for the study by the user. Piling according to the planned construction case may only take place if the r_{PTS}, the PTS-related distance to threshold of the piling, is smaller than r_{safe}. Furthermore, the resulting SEL_{cum} must comply with the relevant acoustic criteria of Table 1. If these criteria are met, all marine mammals are assumed to be at least at distance r_{safe} at the onset of piling and fleeing directly away from the noise with a constant speed (v_{flee}), which in turn means that by the end of the pile driving (for that particular foundation), no animal will have experienced an SEL_{cum} above the PTS onset threshold.

ADD Prognosis

If the planned construction case results in relatively low noise impact, identified as a very short distance to threshold for the onset of PTS, piling is allowed without an ADD, as there is no significant risk of injury to mitigate. Otherwise, and in most cases for large-diameter piles, a separate prognosis must be done, based on the planned ADD as the only noise source. The intention behind the criteria for this ADD prognosis is to avoid the ADD itself having a larger impact than the piling operation.

Fleeing Animal Concept

An important feature of the prognosis concept is that of a fleeing animal, introduced to avoid the unrealistic overestimation of predicted impact if it is assumed that the receiver (animal) remains stationary throughout the entire exposure. A numerical framework is given that represents an animal fleeing radially away from the noise source at a constant speed. At present times, a speed of 1.5 m/s is suggested regardless of species, but alternative values (see, e.g., (Tougaard 2021a)) are permitted as long as they are justified. Its practical use has shown that in terms of SEL_{cum} the numerical difference between a stationary vs. constant speed-fleeing receiver is significant and easily more than 10 dB depending on sound field properties. At the same time as being a better approximation to actual behavior, the moving animal assumption may be regarded as reducing an unwarranted but significant worst-case assumption (of a stationary animal) from the prognosis.

Prognosis Options

It is permitted to base the prognosis on numerical modeling (examples include finite element, parabolic equation, or wavenumber equation schemes) or alternatively using semi-empirical methods. The latter allows for a range of techniques based on artificial sound sources such as airguns.

A general approach stated several places in the guidelines is freedom for choice of method. For several assumptions and methodologies, alternatives are allowed. The requirement is that the user provides adequate justification that the alternative provides similar or better representation than what is stated in the guideline. Examples where this might become relevant are:

- The prognosis formulas for vibratory driving assume constant driving force amplitude over time, which in some cases might be over-simplified. The user might have more detailed information and may modify the SEL_{cum} formulas to accommodate this.
- Similarly, the formulas for impact driving assume a constant time interval between hammer impacts.
- Currently, a fleeing speed of 1.5 m/s is assumed regardless of animal species. If well-documented data justifies other speed(s), these may be used.
- A simple, semi-empirical formula is suggested in the guidelines for correction of differences in applied hammer energy compared to that assumed for the prognosis. The user may apply alternative expressions or approaches for the correction.

Verification Measurements Explained

It is an inherent challenge of the acoustic criteria of Table 1 that the corresponding SEL_{cum} metric is not easily evaluated from measurements during the installation, particularly because the limit values refer to a non-stationary receiver (a fleeing animal). On that background, it is required for the prognosis to prepare certain sets of data that are more readily derived from field measurements. For the transect identified as having the longest distance to threshold for PTS criteria, the following is calculated:

- Single-strike sound exposure level SEL_{ss} in the case of impact driving.
- Sound pressure level SPL in the case of vibratory driving.

At the construction site, measurements must then be made for two purposes:

- Verification of the propagation model used for the prognosis. This is based on evaluation of the transmission loss, which must be demonstrated to match the prognosis data. The guidelines permit both the use of an artificial underwater sound source and the actual pile driving operation.
- Demonstration of compliance with the acoustic criteria, based on the above-mentioned measurable output from the prognosis. These must be prognosticated in 1/3-octave bands and at specified reference ranges. The measured broadband values corresponding to 5% exceedance levels, with and without appropriate frequency weighting, must be reported.

In both contexts, prognosis and measurements must match within tolerances specified in the guidelines. The idea behind the above sequence is to first establish confidence in the acoustic model, which then leads to confidence in the absolute noise levels resulting from the prognosis.

Finally, there is a risk that the hammer protocol (i.e., impact hammer energy vs. time or vibratory force amplitude) assumed in the prognosis deviates to some extent from that applied during the actual installation. A simple expression is provided in the guidelines to correct for such differences if relevant. After that, the SEL_{cum} of the prognosis must be compared to the limit values of Table 1 to demonstrate compliance.

Conclusion

New scientific advances in the knowledge of marine mammal hearing led to a revision of the Danish guidelines for underwater noise. The revision kept the basic approach of the original 2016 version, addressing the cumulative sound exposure level of an animal fleeing at constant speed away from the noise source. However, several additions and modifications were implemented, in particular that of frequency weighting based on auditory groups.

It is believed that the current guidelines' approach is an improved representation of the acoustic impact on marine mammals caused by offshore pile driving.

It is expected that future revisions will accommodate updates to reflect new knowledge. In particular, it is foreseen that behavioral response to underwater noise will become better understood from ongoing and upcoming research.

Acknowledgments This work was funded by the Danish Energy Agency, and a large part of the work was done within a workgroup, which consisted of the authors, as well as Anna-Grethe Underlien Pedersen and Nynne Elmelund Lemming (Danish Environmental Protection Agency) and Søren Enghoff, Danish Energy Agency. Also, the authors would like to thank their colleagues and industry partners who provided valuable feedback to the process.

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