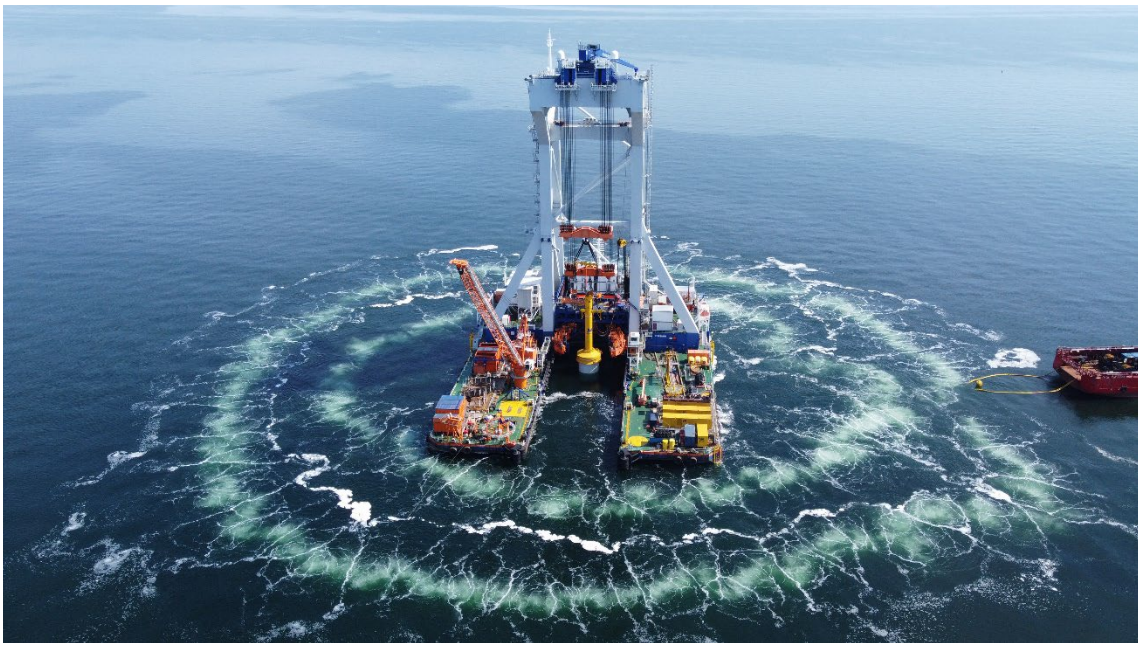
Guideline for underwater noise

Installation of impact or vibratory driven piles

May 2022



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Contents

List of abbreviations

ADD	Acoustic Deterrent Device
BT	Beam Tracing
DTT	Distance-to-Threshold
FE	Finite Element
HF	High Frequency
LF	Low Frequency
MOD	Max-Over-Depth
NM	Normal Modes
PCW	Phocid Carnivores in Water
PL	Propagation Loss
PE	Parabolic Equation
PTS	Permanent Threshold Shift
RMS	Root Mean Square
RT	Ray Tracing
SEL	Sound Exposure Level
SPL	Sound Pressure Level
TL	Transmission Loss
TTS	Temporary Threshold Shift
VHF	Very High Frequency
WI	Wavenumber Integration

Summary and document overview

This Guideline concerns underwater noise in relation to the construction of offshore wind in Danish waters. Technical methods are presented for performing numerical prognosis and measurements. Also, sets of acoustic criteria are stated for compliance. The latter include Permanent Threshold Shift (PTS), Temporary Threshold Shift (TTS), and behavioural impact. The acoustic criteria are based on auditory frequency weighting functions as relevant to species in Danish waters.

Impact pile driving as well as vibratory pile driving installation techniques are addressed, with separate adapted methods for modelling and measurements. Requirements for permitted use of an Acoustic Deterrent Device (ADD) are stated.

Concession Holder shall 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, all either fully numerical or on a semi-empirical basis:

• **Reference Case:**	Worst-case, without noise reduction techniques
• **Planned Construction Case:**	As planned, possibly with noise reduction and ADD
• **Specific ADD Case:**	If relevant, with the ADD as the only active noise source

Depending on the outcome of the Planned Construction Case, the use of an ADD may or may not be permitted within restrictions.

For later direct comparison with measurements during pile installation, the Prognosis shall provide certain acoustic metrics that are suited for direct measurements.

On-site measurements of underwater sound shall be taken with two purposes:

- Verification of propagation model used in the Prognosis
- Demonstration of compliance with acoustic criteria

Assessment of the compliance related measurements involve correction for actual vs. assumed hammer activity.

Document overview

Section 1 defines acoustic metrics and terms used throughout the Guideline. Reference is made to ISO 18405 and 18406.

Section 2 presents a set of acoustic criteria for fulfilment in relation to construction activities. PTS/TTS criteria are based on recent literature, while behavioural criteria are based on new work in relation to this Guideline.

Section 3 specifies terms of use for Acoustic Deterrent Devices (ADDs). The use is mandatory during the construction, with the exception of relatively low-noise scenarios.

Section 4 specifies the requirements of the Prognosis, both fully numerical and semi-empirical. In the latter case, details are given for performing on-site sound propagation measurements. Options are included for either performing curve fit of the sound field, or directly using fine-resolution grid point data. Formulas are given for calculation of SEL_{cum} for a fleeing animal.

Section 5 addresses on-site measurements, for both model verification as well as criteria compliance.

Introduction and scope

In recent years, there has been a growing concern about the effect of underwater noise from human activities on marine mammals. Based on the advice from a previous working group, the Danish 2016 Guideline for underwater noise from installation of impact-driven piles was formed. The Guideline from 2016 [22] only consider impact in the form of permanent impact on the hearing of marine mammals, as the empirical evidence regarding other forms of impact was considered insufficient at the time the Guideline was formed. Further, frequency weighting principles applied to marine mammals were only just becoming an established scientific approach at the time of writing the 2016 Guideline. This has changed in the recent years, and as part of the process leading to this update of the Danish Guideline, relevant scientific evidence has been extracted by DCE in a series of technical reviews [6][7][8] that serve as background reports for this document. The technical reviews from DCE and this Guideline have been discussed in a new working group before being published. The working group consist of following members:

- Professor Jakob Tougaard AU/DCE/ Department of Bioscience, section for Marine Mammal Research
- Principal Consultant René Smidt Lützen, Vysus Denmark A/S
- Special Advisor Anna-Grethe Underlien Pedersen, Danish Environmental Protection Agency
- Advisor Nynne Elmelund Lemming, Danish Environmental Protection Agency
- Special Advisor Søren Enghoff, Danish Energy Agency
- Special Advisor Søren Keller, Danish Energy Agency

The most important changes in this current revision of the Guideline are:

a. Inclusion of behavioural disturbance of marine mammals and
b. Introduction of frequency weighting principles and acoustic criteria according to auditory groups.

Both features are deemed more just and biologically correct in assessments of impacts.

The Guideline now further specifies:

c. Criteria and procedures for use of Acoustic Deterrent Devices (ADD),
d. Adapted procedures for impact and vibratory driving and
e. Calculation of Distance-to-Threshold.

The Guideline relates to a set of standard conditions normally found in the Construction Permit for offshore windfarms. The standard conditions, the Guideline and the DCE background reports can be found on the Danish Energy Agency website, www.ens.dk.

The current 2022 Guideline replaces the former 2016 Guideline with immediate effect.

Scope of the work

For installation of offshore wind turbine foundations, the Concession Holder must demonstrate how it is intended to fulfil the requirements on limitation of environmental impact caused by emitted underwater noise as set forth by The Danish Energy Agency in the Conditions of the Construction Permit. To do this the Concession Holder is required to prepare a Prognosis for underwater noise and use this prognosis as basis for conducting an environmental impact assessment of the potential impact of underwater noise on marine mammals. Furthermore, the Concession Holder must conduct a verification measurement programme. The respective methodologies, requirements, and criteria are described in the present Guideline. The legal framework for the Guideline is The Act on Promotion of Renewable Energy.

The present Guideline addresses impact as well as vibratory pile driving. Other installation techniques, operational wind turbine noise, and vessel noise are beyond the scope. The Guideline furthermore addresses installation of single-type foundations such as monopiles, as well as multi-pile foundations such as jackets and tripods. A procedure is integrated for permitting and assessing the impact of Acoustic Deterrent Devices (ADD) for the context of pile installation.

The Guideline contains acoustic criteria corresponding to Permanent Threshold Shift (PTS) for species relevant to Danish waters. These criteria are stated as cumulative sound exposure level (abbreviated as SEL_{cum}), weighted by appropriate auditory frequency weighting functions.

Also, threshold values for the evaluation of behavioural reactions to underwater noise in harbour porpoises are presented. These are stated as root-mean-square sound pressure levels over 125 ms ($SPL_{125\ ms}$), weighted by appropriate auditory frequency weighting functions.

For direct comparison with measurements during pile installation, the Guideline requires a Prognosis of:

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

The topic of behavioural impacts is expected to be further developed for future revisions of the Guideline. Currently, the Guideline does not assess habitat loss considerations. An example of a method for this is found in [8].

Regardless how the Concession Holder develops a model and derives the approximation for the sound propagation, it is a requirement that an on-site validation shall be conducted.

Furthermore, on-site measurements shall be taken to demonstrate compliance with the acoustic criteria.

1. Definition of acoustic metrics and terms

Metrics definitions are given in ISO 18406 [1] with main features summarized for convenience in the following. For all metrics, frequency weighting as applicable shall be specified.

1.1. Pulse duration

The pulse duration is the percentage energy signal duration over the acoustic pulse, defined in ISO 18406 [1], assuming an energy percentage for the pulse duration of 90%.

1.2. Root-mean-square sound pressure level (SPL) $L_{p,rms}$

This is the Root Mean Square (RMS) of the sound pressure taken over a time interval $T=t_2-t_1$ [s]. The related level in dB is often referred to as “equivalent continuous sound pressure level”, (symbol: L_{eqT}) over time interval T. The sound pressure level is abbreviated as SPL.

Starting from the Mean Square average sound pressure p_{ms}, [Pa^2] the RMS pressure p_{rms} [Pa] follows as:

$$p_{ms} = \overline{p^2} = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} p^2(t)dt$$

The RMS sound pressure level (abbreviated as SPL, symbol: $L_{p,rms}$) in dB is then:

$$L_{p,rms} = 20\log\frac{p_{rms}}{p_0}\ dB$$

The reference value for underwater sound pressure is p_0=1 μPa.

For the purpose of evaluating behavioural reactions to the noise, the RMS-sound pressure level calculated over a time interval corresponding to the average integration time of the mammalian ear (125 ms) is appropriate [7].

If the duration of the individual pile driving pulses are less than 125 ms, the corresponding SPL over 125 ms (abbreviated as $SPL_{125\ ms}$) can be estimated from the SEL_{SS} (defined in Section 1.4):

$$L_{p,rms,125ms} = L_{E,p} + 10\log_{10}(0.125) = L_{E,p} + 9\ dB$$

1.3. Sound exposure level (SEL)

The general definition of sound exposure level (abbreviation: SEL) is given in ISO 18405 [2].

1.4. Single-strike sound exposure (SEL$_{ss}$) L$_{E,p}$

The single-strike sound exposure level (abbreviation: SEL$_{ss}$) is defined in ISO 18406 [1] for a specific acoustic pulse, or event. In this Guideline, a pulse duration definition based on 90% energy shall be applied (see Section 1.1). The reference value is 1 µPa^{2}s.

There may be practical cases where the pulse duration exceeds the period between hammer strikes, leading to overlapping pulses. In this case, as described in ISO 18406 [1], the integration time for SEL$_{ss}$ shall be chosen to be the period between hammer strikes. The mean SEL$_{ss}$ for such a pulse sequence may be obtained by integrating over the entire pulse sequence and dividing by the number of pulses.

1.5. Cumulative sound exposure (SEL$_{cum}$) L$_{E,cum}$

The single-strike sound exposure (abbreviation: SEL$_{cum}$, symbol: L$_{E,cum}$) from individual acoustic events such as hammer strikes can be summed up over a specified duration (such as the full pile installation) to form the cumulative sound exposure (abbreviation: SEL$_{cum}$, symbol L$_{E,cum}$) as:

$$L_{E,cum} = 10\log_{10}\frac{E_{cum}}{E_0}\ dB$$

Here, E$_{cum}$ is the cumulative sound exposure for N acoustic pulses, each with single-strike sound exposure E$_n$ as:

$$E_{cum} = \sum_{n=1}^{N} E_n$$

The reference value E$_0$ is 1 µPa^{2}s.

1.6. Source level (SL$_E$ and SL) L$_{S,E}$ and L$_S$

Detailed definitions of source levels are given in ISO 18405 [2] and only briefly summarized here.

For a transient source, the sound exposure source level with symbol L$_{S,E}$ [dB re 1 µPa^{2}m^{2}s] is the time-integrated squared sound pressure level at a distance of 1 m from a hypothetical point source, placed in an (hypothetical) infinite uniform lossless medium, and with the same sound exposure source level as the true source. In the literature, this metric is sometimes in practice cited as a source level with reference value of 1 µPa^{2}s@1m.

Similarly, for a continuous source the source level L$_S$ [dB re 1 µPa^{2}m^2] is the time-integrated squared sound pressure level at a distance of 1 m from a hypothetical point source, placed in an (hypothetical) infinite uniform lossless medium, and with the same sound pressure source level as the true source. If using the equivalent root source factor definition, the reference for L$_S$

becomes 1 µPa·m. In the literature, this metric is sometimes cited as source level with reference value of 1 µPa@1m.

The source level can be determined by adding the propagation loss to the measured SPL or SEL.

1.7. Propagation loss $N_{PL,E}$ and N_{PL}

The propagation loss is either based on SEL (symbol: $N_{PL,E}$) or SPL (symbol: N_{PL}) and is defined in detail in ISO 18405 [2] but briefly summarized here.

The propagation loss relates the level at a distance r to the corresponding source level:

$$N_{PL,E}(r) = L_{S,E} - L_{E,p}(r)\ dB$$

$$N_{PL}(r) = L_S - L_p(r)\ dB$$

In both cases, the reference value is 1 m^2.

1.8. Transmission loss ΔL_{TL}

With symbol ΔL_{TL} (abbreviation: TL) this is the reduction in a specified level between two specified points r_1, r_2 that are within an underwater acoustic field.

$$\Delta L_{TL} = L(r_1) - L(r_2)\ dB$$

By convention, r_1 is chosen to be closer to the source than r_2, hence leading to usually positive values of the transmission loss.

For the detailed definition, see ISO 18405 [2].

1.9. Max-Over-Depth across water column

For the purpose of this Guideline, Max-Over-Depth is defined. For a fixed range step r_i, the maximum metric value across the water column is observed, 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 shall be considered.

1.10. Distance-To-Threshold

Typically evaluated from a Max-Over-Depth parameter (Section 1.9), Distance-To-Threshold (abbreviated DTT) compares the range dependent variation of the parameter to a given acoustic threshold value.

Distance-To-Threshold is that radial distance from the source within which the acoustic criteria would be exceeded. It should be noted that the sound field in shallow-water acoustic environment usually decays with distance in a non-monotonous manner, see comments in Section 5.3. Care must be taken in the numerical evaluation to avoid identifying local features as the global DTT of the transect.

1.11. Background noise

The background noise is defined as all sound recorded by the hydrophone in the absence of the pile driving signal for a specified pile driving acoustic signal being measured (ISO 18406 [1]).

Measured metrics that exceed the background noise by more than 3 dB shall be corrected e.g. using an energy-based approach, and the method of correction shall be described (see e.g. the method in Section 10.4 of ISO 1996-2 [3]). Measured metrics that exceed the background by less than 3 dB shall be used without correction, providing an upper boundary estimate. If such data are reported and used, this shall be commented in the report.

1.12. Exceedance level

For a sound related parameter L_x, the Exceedance level in dB corresponding to a percentage x is the level which is statistically exceeded x % of the time during the observation period, e.g. the pile installation sequence. As an example, L_{90} is the level which is exceeded in 90% of the observations. Similarly, L_{50} is the level which is exceeded in 50% of the observations (also referred to as the Median).

1.13. Definition of impulsive sounds vs. other sounds

For the purpose of assessment of risk of hearing loss to marine mammals, sounds are separated into type-I sounds (“impulsive sounds” in [4]) and other sounds. Type-I sounds are characterized by the following three criteria:

- Very fast onset, often, but not always, followed by a slower decay.
- Short duration, fraction of a second.
- Large bandwidth.

Some sounds fulfil two, but not all three conditions (typically narrow-bandwidth signals). These signals are referred to as P-type sounds (“non-pulses” in [5]). The distinction between the different types is not clear but is of importance because it is recognized that type-I sounds have greater potential to induce hearing loss than P-type and other sounds and therefore raises a need for separate exposure limits.

Examples of type-I sounds are underwater explosions, seismic air guns and impact pile driving. For the purpose of this Guideline, sound produced by vibratory pile driving is regarded as other sounds.

A detailed discussion of this topic is given in [7].

1.14. Frequency spectrum and broadband levels

For both modelling and measurements, the signals must be analysed both to obtain broadband (i.e. overall) levels as well as 1/3-octave band spectral levels. The recommended data processing steps are given in ISO 18406 [1].

1.15. Auditory frequency weighting

Animals do not hear equally well at all frequencies. Marine mammals are classified according to a limited number of functional hearing groups in [4], where separate auditory frequency weighting functions have been defined based on hearing abilities. These weighting functions are used in assessments of risk of impact. For species that are relevant in a Danish context (see later in Table 3), the hearing groups are [7]:

- Low-frequency (LF) cetaceans
- High-frequency (HF) cetaceans
- Very high-frequency (VHF) cetaceans
- Phocid carnivores in water (PCW)

The frequency dependent weighting functions W(F) with F being the frequency in kHz are described by:

$$W(f) = C + 10\log_{10}\left(\frac{(F/F_1)^{2a}}{[1+(F/F_1)^2]^a \cdot [1+(F/F_2)^2]^b}\right)\ dB$$

Parameters for the individual functional hearing groups are given in Table 1. The respective weighting functions are plotted in Figure 1.

Hearing group	a	b	F1	F2	c
LF	1	2	0.20 kHz	19 kHz	0.13 dB
HF	1.6	2	8.8 kHz	110 kHz	1.20 dB
VHF	1.8	2	12kHz	140 kHz	1.35 dB
PCW	1	2	1.9 kHz	30 kHz	0.75 dB

Table 1: Parameters for auditory weighting functions of hearing groups relevant to Danish waters. Data from [4].

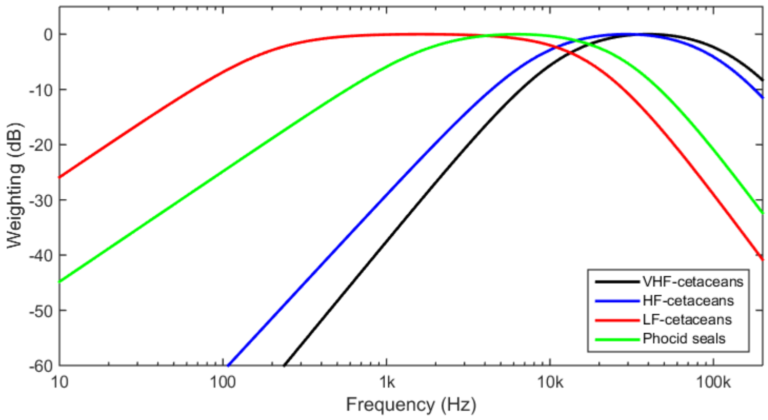

Figure 1: Frequency weighting functions proposed by [4] and [7] for auditory groups relevant to Danish waters.

A signal, which contains all or most energy in a narrow frequency band can simply be weighted by adding the corresponding weighting value from the appropriate weighting curve of Figure 1 at the relevant frequency. For cases such as piling, where the noise contains energy in a wider frequency range it is required to filter the signal with a filter corresponding to the appropriate weighting function. See [7] for additional information, and a method for time domain application. Note that this method must be adapted to current weighting functions with the parameters listed in Table 1.

It is important to note that in Table 1, F1 and F2 are characteristic frequencies of the curve shapes and may not be interpreted as upper/lower limits of the hearing. For convenience, practical indicative hearing ranges were derived in [8] and summarized in Table 2. Note that no empirical hearing data are currently available for the LF group. For the practical purposes of this Guideline, the estimate presented in Table 2 is based on a Minke whale as proxy for the LF group [8].

Hearing group	**Indicative hearing range**
LF (Minke whale)	10 – 34,000 Hz
HF	1,000 - 120,000 Hz
VHF	1,000 – 150,000 Hz
PCW	40 – 50,000 Hz

Table 2: Practical, indicative frequency ranges for hearing of auditory groups relevant to Danish waters [8].

2. Acoustic criteria for compliance

Table 3 and Table 4 list the threshold values for species identified as relevant in Danish waters [6], corresponding to I-type and other sounds, respectively. The thresholds given as SEL_{cum} represent acoustic criteria for Permanent Threshold Shift (PTS) and Temporary Threshold Shift (TTS) [7]. An additional SPL threshold is shown for Behavioural Disturbance (presently only for Harbour porpoises) [8]. While the latter threshold was derived for I-type sounds, it may for the time being be applied also for other sounds. It is permitted to use alternative threshold values in which case these must be justified.

The PTS and TTS thresholds were derived from [4] and reviewed by [7] against more recent experimental data and apply until further notice.

In the tables, PTS and TTS threshold values are given as SEL_{cum} with the respective auditory weighting functions (Section 1.15). Hence, subscript “xx” of metrics $L_{E,p,xx,24h}$ refer to either LF, HF, VHF, or PCW. Similarly, the Behavioural Disturbance stated as SPL shall be evaluated for the corresponding auditory weighting function.

SEL_{cum} shall be evaluated for each foundation over the entire installation period, with a maximum of 24 hours. See additional considerations in Section 4.9.

It is the responsibility of the Concession Holder to determine which and how many of the species listed in Table 3 and Table 4 shall be considered. This selection should be based on the presence/absence of the indicated species in the concession area. As a starting point, the overview in [6] may be consulted for background.

Both thresholds for PTS, TTS, and Behavioural Disturbance shall be evaluated. As an acoustic criterion, the stated PTS thresholds shall not be exceeded for a fleeing animal under the following conditions:

- Animal having starting position greater than r_{safe} at any location in and around the Concession area within a radius as described in Section 4.2.
    - Here, r_{safe} is the distance within which the Concession Holder estimates that no animals of Table 3 are present prior to the pile driving activity. The Concession Holder shall justify the assumed value of r_{safe}.
- During the installation of any single foundation. In practice, the Concession Holder will often base the assessments on a limited number of foundation positions. In this case, it must be justified why these are representative of the full array of planned foundations.

I-type sounds					
Species (English)	**Species (Danish)**	**Weighting**	**Threshold type**		
			PTS	**TTS**	**Behavioural Disturbance**
			SEL_{cum} $L_{E,p,xx,24h}$	**SEL_{cum} $L_{E,p,xx,24h}$**	**SPL $L_{p,rms,125ms}$**
Harbour porpoise	Marsvin	VHF	155	140	103
White-beaked dolphin	Hvidnæse	HF	185	170	-
Pilot whale	Grindehval	HF	185	170	-
Minke whale	Vågehval	LF	183	168	-
Harbour seal	Spættet sæl	PCW	185	170	-
Grey seal	Gråsæl	PCW	185	170	-

Table 3: Species of marine mammals commonly occurring in Danish waters with corresponding auditory groups and respective acoustic thresholds stated as SEL_{cum} in dB re 1 µPa^{2}s and SPL in dB re 1 µPa. Only thresholds for I-type sounds are shown.

Other sounds					
Species (English)	**Species (Danish)**	**Weighting**	**Threshold type**		
			PTS	**TTS**	**Behavioural Disturbance**
			SEL_{cum} $L_{E,p,xx,24h}$	**SEL_{cum} $L_{E,p,xx,24h}$**	**SPL $L_{p,rms,125ms}$**
Harbour porpoise	Marsvin	VHF	173	153	$^{*)}$103
White-beaked dolphin	Hvidnæse	HF	198	178	-
Pilot whale	Grindehval	HF	198	178	-
Minke whale	Vågehval	LF	199	179	-
Harbour seal	Spættet sæl	PCW	201	181	-
Grey seal	Gråsæl	PCW	201	181	-

*Table 4: Species in Danish waters with corresponding auditory groups and respective acoustic thresholds stated as SEL_{cum} in dB re 1 µPa^{2}s and SPL in dB re 1 µPa. Only thresholds for sounds other than I-type are shown. *)Threshold for Behavioural Disturbance is a coarse estimate, to be used only until better data become available.*

3. Acoustic Deterrent Device

In the context of offshore piling, an Acoustic Deterrent Device (ADD) serves as a marine mammal mitigation technique. Ideally, it deters animals from potential injury zones [9].

The use of an ADD is mandatory during the construction sequence of any single foundation, with the exception of relatively low-noise scenarios as specified in the case $r_{PTS}<200$ m of Figure 2.

The ADD shall be activated at least 15 minutes before pile installation startup. If the pile installation is inactive for more than 2.5 hours, the ADD shall have been active for another 15 minutes before installation may start again. This procedure follows suggestions presented in [10].

As the ADD is inherently a significant source of underwater noise, its acoustic impact shall be assessed. A procedure for doing so is an integral part of the current Guideline Prognosis (see Section 4.1.1).

4. Requirements for Prognosis

4.1. General prognosis concept

The two main components of the Prognosis are the noise source characteristics and the sound propagation characteristics. Further, the duration of the pile driving activity and the hammer action will have bearing on the cumulated noise and shall be described. For impact driving the expected employed hammer energy and number of blows, as well as the time interval between blows, will have bearing on the cumulated noise and shall be described. For vibratory driving, the hammer's driving force amplitude shall be described.

The Prognosis can be based either entirely on numerical modelling (e.g. Finite Element, Parabolic Equation, Wavenumber Equation type of modelling) or semi-empirically based estimation. The Prognosis shall be calculated for a specific number of piles as requested in the Conditions, and along multiple transects.

The objective of the Prognosis is for the Concession Holder to estimate the environmental impact using the given sound source and propagation properties and calculate the cumulative SEL experienced by a receptor (marine mammal) while it is fleeing away from the noise source.

Hence, until further notice, the calculation constant for fleeing speed stated in Table 5 applies to all Prognosis approaches of this Guideline and for all animal species. Alternative values may be applied, in which case their use must be justified in the Prognosis report. Some examples of alternative fleeing speeds for different species are found in [8].

Constant name	Symbol	Value
Animal fleeing speed	v_f	1.5 m/s

Table 5: General constants for SEL_{cum} prognosis.

4.1.1. Required Prognosis scenarios

As illustrated in the flow diagram of Figure 2, a minimum of three prognosis scenarios shall be addressed:

1. Reference Case (unmitigated)
2. Planned Construction case (potentially including noise reduction)
3. Specific ADD Case

The scenarios are described in general terms in the following, while detailed requirements for the Prognosis implementation is given in subsequent sections.

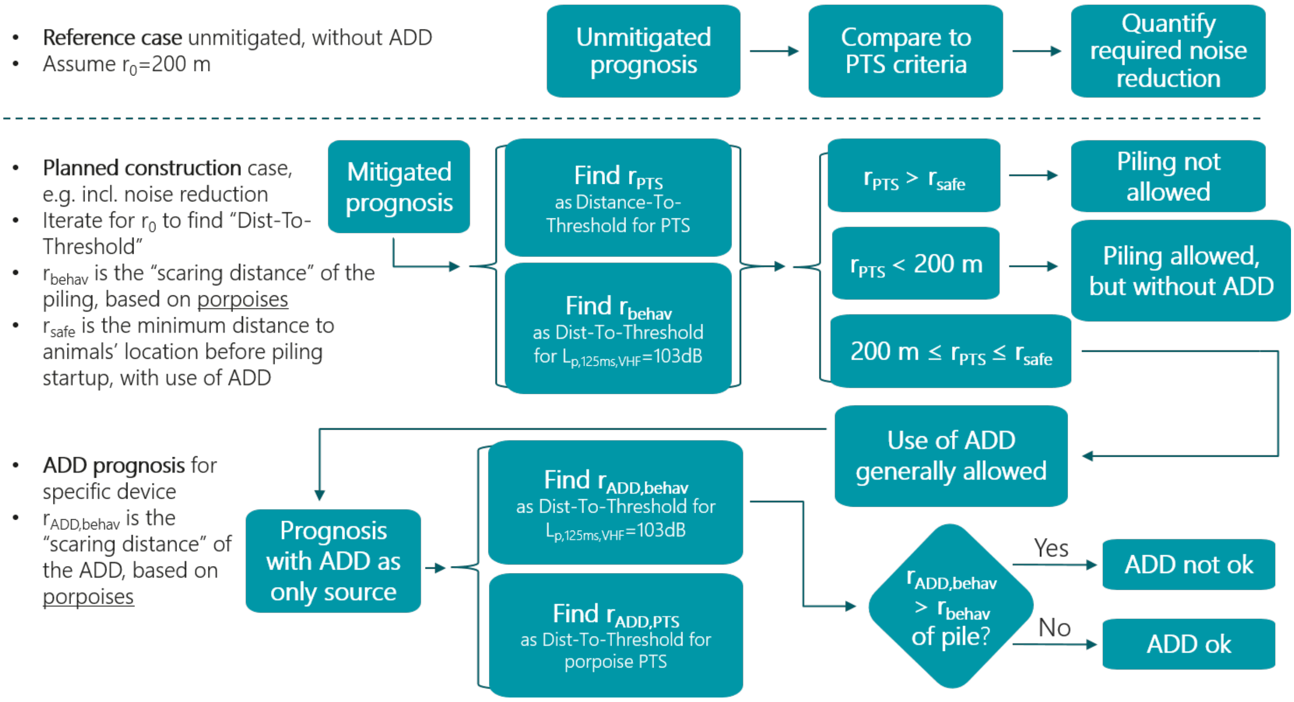

Figure 2: Overview flow diagram for prognosis scenarios.

Reference Case

This case represents a practical worst-case scenario of the piling operation. It assumes the piling to be performed without noise reduction techniques (Section 4.1.3), and without ADD (Section 3). It may be thought of as characterising the piling situation with simultaneous failure of both noise mitigation means and ADD.

For the Reference Case, it shall be assumed that the fleeing animal starts at a position of r_0=200 m away from the pile. The SEL_{cum} with appropriate frequency weightings shall be determined and compared to the PTS of the project relevant auditory groups (Section 2). The outcome is a quantification of minimum required noise mitigation. It is noted that evaluation of TTS and behavioural criteria is not mandatory for the Reference Case.

Planned Construction Case

A separate Prognosis must be performed describing the scenario actually planned by the Concession Holder. This may or may not include noise reduction means. The Planned Construction Case assumes the piling operation to be the only active noise source in the Prognosis model. For this setup, an iteration over animal starting position r_0 shall be performed to determine the Distance-to-Threshold (DTT, see Section 1.10), labelled as r_{PTS}, corresponding to PTS criteria for the project relevant auditory groups of Section 2. As described in Section 2 the resulting value of r_{PTS} shall not exceed r_{safe}, which is the minimum expected distance to the animals before piling onset, and following 15 minutes use of an ADD if relevant (see Section 3). The assumed value of r_{safe} shall be justified.

Similarly, the DTT of the $SPL_{125\ ms}$ behavioural criteria stated in Table 4 shall be determined, corresponding to r_{behav}.

A general check of ADD permission shall be performed to ensure that an ADD will not unnecessarily worsen the acoustic impact:

- Only if r_{PTS} (for all relevant auditory groups) related to the piling is larger than 200 m, use of an ADD is in principle allowed. Then the specific ADD Prognosis shall be carried out, see below.
- If r_{PTS} (for all relevant auditory groups) is smaller than 200 m, the use of an ADD is not permitted.

Construction according to the Planned Construction Case can only be approved if r_{PTS} is less than r_{safe}.

Specific ADD Case

If the general use of an ADD was permitted in the Planned Prognosis Case (see above), a separate noise Prognosis shall be performed assuming the specific ADD as the only active noise source (i.e. no piling source). This version of the Prognosis is done analogously with those for the pile installation, but only considering the ADD. Here, device specific source level (as frequency spectrum) e.g. from vendor data shall be used as input to a Prognosis. An evaluation against VHF auditory group weighting shall be performed:

DTT shall be determined for the harbour porpoise PTS criteria, for documentation.

Similarly, the DTT corresponding to the behavioural criteria $SPL_{125\ ms}$ of Table 3 and Table 4 shall be determined, which is $r_{ADD,behav}$. Then, a comparison of the behavioural impact is done for the piling source vs. the ADD:

- Only if $r_{ADD,behav}$ is smaller than r_{behav} of the piling source, use of the specific ADD is permitted.
- Alternatively, if $r_{ADD,behav}$ is larger than or equal to r_{behav} a different ADD device must be considered and evaluated.

4.1.2. Option of curve fit or fine-resolution assessment for SEL_{cum}

Once a representation of the underwater sound field is established, the cumulative SEL onto the fleeing receiver must be evaluated by marching through the sound field. This may be done either point-by-point throughout the calculation grid in case of a fine-resolution numerical model, or by use of a curve-fit expression. The corresponding approaches for impact and vibratory driving are detailed later in this section.

4.1.3. Noise reduction

Reducing the risk of impact to marine ecosystems can be achieved by reducing the amount of noise pollution. Generally, there are two approaches to noise reduction:

- Primary means: Direct mitigation of the noise generating mechanism. Examples include noise optimized piling schemes and use of alternative hammer technologies, and impact pulse prolongation devices.
- Secondary means: Introduction of noise barrier in the propagation path. Examples include bubble-curtains, air-filled bladders, and double-walled steel cylinders.

For background information, at the time of writing this Guideline, recent overviews of available technologies were given in [12],[13], and [14].

If necessary, the Concession Holder shall propose noise reduction measures, which ensures compliance with the relevant PTS thresholds of Section 2.

The Concession Holder may freely choose between primary and secondary noise mitigation measures or a combination hereof.

4.1.4. On-site measurements for compliance verification

Measurements shall be taken on the construction site for two purposes:

- Verification of the propagation model used for the Prognosis, see Section 5.1.
- Demonstration of compliance with acoustic criteria, see Section 5.3.

4.2. Hydrographic variation

In some Danish waters such as the North Sea, a well-mixed condition is common, leading to relatively stable sound speed profiles with little variation over depth. However, in inner waters and the Baltic Sea, stratification occurs frequently (and temporally unstable) and may have a significant impact on the sound speed profile. The latter is governed by temperature and salinity profiles over the water column, see e.g. [15] for a simple relation.

For project sites with significant hydrographic variation over the course of the planned construction, separate Prognoses shall be prepared to address the expected extremes. It is the responsibility of the Concession Holder to select a suitable set of Prognosis cases for this purpose.

4.3. Radial transects

The Prognosis shall include a number of radial transects originating from the foundation position. For assessment against PTS or TTS criteria each transect must have a minimum length of 10 km. For behavioural disturbance, the recommended minimum transect length is 50 km. However, Concession Holder may choose a transect length sufficiently long to address the behavioural disturbance. It is noted that for the Reference Case (Section 4.1.1) the DTT for behavioural disturbance is not required.

In all cases, the calculation shall be truncated at the distance at which the transect reaches the shoreline, if relevant.

4.4. Frequency range and resolution for Prognosis

Generally, the Prognosis must address a broad frequency band corresponding to the auditory group(s) relevant to the project. However, some of the noise reducing means described in Section 4.1.3 may significantly affect the spectral shape of the received noise. Hence, according to the considered construction case the Prognosis must address the frequency ranges as described in Table 6.

Construction case	Frequency range
Unmitigated piling, or with frequency independent noise reduction	According to Table 2 for the relevant auditory groups
Piling with frequency dependent noise reduction means	40 Hz to 150 kHz

Table 6: Required frequency range for Prognosis according to different construction scenarios.

If the full frequency range specified in Table 6 cannot be directly implemented, assumptions regarding the non-modelled frequency range shall be presented and justified in the Prognosis report.

As described in Section 1.14, the modelled range must be addressed both using broadband levels and 1/3-octave band levels. However, in recognition of the generally lower availability of qualified source and environmental data for the high kHz frequency range, it is permitted to address the range above 2 kHz in 1/1-octave bands.

4.5. Model requirements

Regardless of type of model (numerical or semi-empirical), a list of requirements shall be fulfilled as described in the sections below. In exceptional case of deviations, these must be discussed and justified in the prognosis report.

4.5.1. Noise source characterization

The following shall be described and quantified in the Prognosis report:

- Unweighted spectrum of piling source. This typically represents a position from a source model within tens of metres from the pile, or back-propagated from far-field measurements (note here the difference between Transmission Loss and Propagation Loss, Sections 1.7 and 1.8).
    - If the prognosis method uses point sources as input, the approach for estimating these source levels must be described, including the assumed source depth.
- The variation of source forcing properties.
    - For impact piling, this is hammer energy, e.g. as presented in the simplified hammer protocol example of Table 7. This can be thought of as a proposed driving "history" and may be provided both as tables or curves including planned non-driving intervals if any.
    - For vibratory driving, this is driving force. A time/depth-varying force amplitude may be accounted for, as in the impact piling example.

It is recommended to furthermore document:

- Variation of noise source metrics across water depth.
- Variation of noise source metric as a function of pile penetration during installation.

Hammer energy [kJ]	**Blow count**	**Hammer energy relative to max energy, S_i**
600	400	15%
800	1400	20%
1600	1400	40%
2400	1400	60%
3200	1400	80%
4000	1200	100%
Total:	7200	
Installation time:	6 hours	
Ramming frequency:	1 strike per 2 s	

Table 7: Example of coarse hammer protocol for impact driving without planned periods of inactivity. The sequence is chronological, from top to bottom. This is an example only and shall not be used for project purposes. Note that non-constant time intervals, or ramming frequency, between strikes may also occur.

4.5.2. Sound propagation characterisation

The sound propagation shall preferably account for:

- Both compressional and shear waves in the seabed.
  Particularly the top-most seabed layer has significant impact on the acoustic coupling between water and seabed, as well as the sound wave attenuation. The report must

state the assumed geo-acoustic profile, at least with attenuation properties and sound speeds for each layer.

- Boundary conditions at the surface either presuming calm weather or include a surface roughness
- Sea water volume attenuation, at least for frequencies above 2 kHz
- Bathymetry (i.e. water depth variation vs. range) specific to each transect. A depth chart of the bathymetry covering the modelled area shall be included.
- Water sound speed profile (i.e. variation of sound speed vs. depth).

All properties listed above shall be described and quantified in the Prognosis report by means of tables and/or plots. If one or more of these properties are not directly accounted for, the consequence shall be discussed and justified in the Prognosis report.

4.5.3. Particular requirements for numerical prognosis

The horizontal resolution, i.e. grid-point spacing for the sound propagation model shall be 20 m or less (i.e. finer). In vertical direction, grid-points distributed across the water column shall be separated by maximum 1 m, preferably less.

The choice of numerical model must be described in detail and justified in the Prognosis report with respect to its suitability. It is recognized that the required large frequency range may lead to the use of different models for partial frequency ranges. A non-exclusive list of exemplary model types is Finite Element (FE), Parabolic Equation (PE), Normal Modes (NM), Wavenumber Integration (WI), Ray/Beam Tracing (RT/BT).

A minimum of 18 transects shall be modelled. A higher number is recommended.

4.5.4. Particular requirements for semi-empirically based prognosis

The site and transect specific sound propagation properties may be obtained from measurements, using an artificial sound source e.g. an airgun, and multiple receiver positions.

Due to pronounced acoustic interference patterns at low frequencies, the semi-empirical approach here described is not suited for the LF auditory group.

4.5.4.1. Transect propagation measurements for prognosis input

The transect measurements shall be performed by short duration hydrophone deployment at a number of different distances. The applied broadband sound source shall be demonstrated to produce received spectral levels that are above ambient (i.e. background) noise by more than 3 dB for the relevant frequency range, see Table 2. Correction for background noise shall follow Section 1.11.

A minimum of 4 transects shall be investigated (which is fewer than for the purely numerical-based prognosis), and it shall be justified in the Prognosis report that these are the ones expected to produce the highest noise levels.

Reference data shall be recorded at 750 m distance ±5%, using this as a reference distance.

For a given source position, a minimum set of receiver ranges are: 750 m, 1,000 m, 1,500 m, 2,000 m, and 3,000 m. It is recommended to furthermore include a receiver between 5 and 10 km.

The receiver positions shall not deviate from a straight line originating from the source by more than 25 m perpendicular to the straight line.

Horizontal receiver positions shall be determined with an uncertainty of 5% or better.

For each receiver position, measurements must be taken at two hydrophone depths: 50% and 75% water depth (measured from sea surface). Vertical receiver positions in terms of distance from the source shall be determined with an uncertainty of 5% or better.

During the measurements at sea, the water sound speed profile across the water column must be measured at least once per 4 hours of acoustic measurement activity.

Requirements for the acoustic measurement equipment is found in Appendix A.

The measurements shall be analysed as SEL_{ss} and combined into transmission loss using a numerical curve-fit to the expression:

$$\Delta L_{TL} = X_{TL} \cdot \log_{10}(r) + A_{TL} \cdot r \, dB$$

Here, X_{TL} [-] is a positive and A_{TL} [m^{-1}] a positive or negative constant, and r the distance [m]. Separate fits must be made for individual transects and hydrophone depths. It is noted that the curve-fit will typically involve an intermediate, non-zero offset, specific to the sound source. Only X_{TL} and A_{TL} are used for ΔL_{TL}.

Tables of fitted constants X_{TL} and A_{TL} must be prepared for each 1/3-octave band. The reliability of each band shall be assessed, and comments shall be made for bands that do not provide realistic fitted constants. In this context, some limitations should be expected for high-kHz frequencies and long distances.

If the transmission loss ΔL_{TL} is used for the Prognosis as, or converted to, propagation loss N_{PL} or $N_{PL,E}$, the corresponding assumptions must be stated and discussed.

4.6. Reference positions for SEL_{ss} and SPL, and reference TL

From the prognosis, the transect resulting in the longest Distance-To-Threshold for PTS criteria shall be identified as the most critical.

For comparison with the subsequent field measurements, the Prognosis shall include for the most critical transect, at ranges 750 m, 1500 m, and 3000 m:

- For impact driving: single-strike sound exposure level SEL_{ss} and SPL_{125ms}
- For vibratory driving: sound pressure level SPL

The prognosticated metric shall be presented as 1/3-octave band spectra as well as unweighted broadband values, as a minimum corresponding to nominal hammer forcing parameters (impact hammer energy, or the vibratory hammer's driving force). In addition, broadband values of $\text{SEL}_{ss,xx}$, SPL_{xx} and $\text{SPL}_{xx,125\,ms}$ shall be prepared, with frequency weightings xx according to Table 1 for the species relevant to the project.

The presented values shall correspond to the statistical 5% exceedance level.

Furthermore, separate curve fits shall be made for each unweighted 1/3-octave band of the prognosticated metric (SEL_{ss} or SPL) to a reference transmission loss according to:

$$\Delta L_{TL} = X_{TL} \cdot \log_{10}(r) + A_{TL} \cdot r\ dB$$

Here, X_{TL} [-] is a positive and A_{TL} [m^{-1}] a positive or negative constant, and r the distance [m]. It is noted that the curve-fit will typically involve an intermediate, non-zero offset. Only X_{TL} and A_{TL} are used for ΔL_{TL}.

Separate fits must be made for individual transects, and for receiver depths corresponding to 50% and 75% water depth (measured from sea surface). The receiver depths shall be decided from the shallowest reference position. As an example, if the shallowest position has water depth of 32 m the TL curve fits shall be made at 16 and 24 m depth.

Tables of fitted constants X_{TL} and A_{TL} must be prepared for auditory group of Table 1 that are relevant to the project. The quality of each fit shall be assessed, and comments shall be made for auditory groups that do not provide realistic fitted constants. In this context, some limitations should be expected for high-kHz frequencies and long distances.

4.7. Impact driving: Prognosis of cumulative SEL and DTT

To represent a simplified case of a fleeing animal, it is assumed that the receptor moves radially away from the noise source at constant speed v_f and starting at initial distance r_0.

The SEL is numerically cumulated as the receiver moves away along the transect and receives new partial doses for each range step. The calculation is truncated in case the transect reaches shore (Section 4.3).

For the receptor at range r_i [m] from the source, the sound exposure contribution at that range step is E_i [Pa^{2}s]. For the full piling sequence, the cumulative SEL in dB re 1 µPa^{2}s becomes:

$$L_{E,cum} = \log_{10}\frac{E_{cum}}{E_0} = 10 \cdot \log_{10}\frac{\sum E_i}{E_0}\ dB$$

Here, E_0=1 µPa^{2}s is the reference value for sound exposure.

At time t_i after piling onset, the receptor is at range $r_i=r_0+v_f \cdot t_i$.

For the Reference Case of Section 4.1.1, the Prognosis is carried out assuming r_0 = 200 m.

For the Planned Construction Case and Specific ADD Case of Section 4.1.1, an iterative procedure shall be applied for determining $L_{E,cum}$ as a function of r_0. This relation is then evaluated for Distance-To-Threshold (DTT) of the acoustic criteria as described in Section 4.1.1. The process is illustrated schematically in Figure 3.

For both the Planned Construction case and Specific ADD case, DTT must similarly be determined for behavioural disturbance. The procedure is done for $SPL_{125\ ms}$, which is estimated from SEL_{ss}, see Section 1.2

In the following, all metrics shall be calculated per 1/3-octave frequency band with appropriate frequency weighting according to Section 1.15. Hence, in $SEL_{cum,xx}$ the subscript xx refers to the auditory weightings LF, HF, VHF, or PCW in the following.

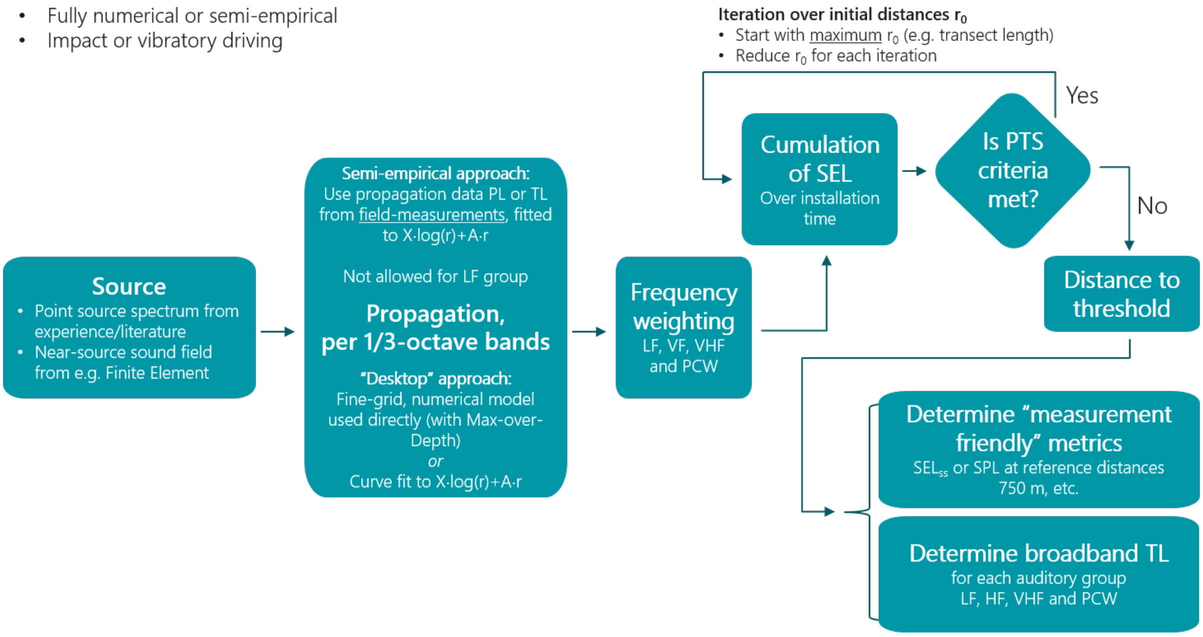

Figure 3: Overview flow diagram showing iterative procedure for Distance-To-Threshold.

4.7.1. $\mathrm{SEL}_{\mathrm{cum}}$ calculation based on $N_{PL,E}$ curve fit

Due to issues related to acoustic interference patterns at low frequencies, the curve fit method of this section is not suited for the LF auditory group.

As mentioned in Section 4.5.4.1, a measurement-based transmission loss ΔL_{TL} [dB] may be curve fitted to an expression of the type $\Delta L_{TL}=X_{TL}\cdot \mathrm{Log}_{10}(r)+A_{TL}\cdot r$.

In the following it assumed that an analogous fit has been obtained for propagation loss $N_{PL,E}$ [dB re 1 m^2]:

$$N_{PL,E} = X \cdot \log_{10}(r) + A \cdot r \ dB$$

Here, X [-] is a positive constant, and A [m^{-1}] is a positive or negative constant.

Assuming the noise to be emitted from an equivalent point source of sound exposure source level $L_{S,E}$ [dB re 1 μPa^2m^2s], the received single-strike SEL at any range r [m] is calculated as $L_{S,E}$ minus $N_{PL,E}(r)$.

Let the unweighted source level $L_{S,E}$ [dB re 1 μPa^2m^2s] corresponding to 100% impact hammer energy be:

$$L_{S,E} = 10 \cdot \log_{10} \frac{E_{100\%}}{E_0} \ dB$$

The energy of the i'th strike out of a total of N strikes is related to the maximum energy by:

$$E_{i\%} = \frac{S_i}{100\%} \cdot E_{100\%}$$

Here, S_i is the percentage of full hammer energy of the i'th strike, see also the hammer protocol example of Table 7.

By a receptor at distance r_i [m] from the source, the sound exposure dose received from the i'th strike will depend on the hammer energy of the i'th strike as well as the propagation loss and thus be:

$$E_{i\%} = \frac{S_i}{100\%} \cdot E_0 \cdot 10^{\frac{L_{S,E}-N_{PL,E}}{10}}$$

In this, the sound exposure-based propagation loss $N_{PL,E}$ is approximated as

$$N_{PL,E}(r_i) = X \cdot \log_{10} r_i + A \cdot r_i = X \cdot \log_{10}(r_0 + v_f \cdot r_i) + A \cdot (r_0 + v_f \cdot t_i) \ dB$$

The $\mathrm{SEL}_{\mathrm{cum}}$ becomes:

$$L_{E,cum} = 10 \cdot \log_{10} \sum_{i=1}^{N} \frac{S_i}{100\%} \cdot 10^{\frac{L_{S,E}-X\cdot\log_{10}(r_0+v_f\cdot t_i)-A\cdot(r_0+v_f\cdot t_i)}{10}} \ dB$$

All hammer strikes of the hammer protocol within a maximum of 24 hours shall be included in $\mathrm{SEL}_{\mathrm{cum}}$.

For values of fleeing speed v_f, see Table 5.

If $L_{S,E}$ is prognosticated at several depths, the largest value must be used for the calculation of $\mathrm{SEL}_{\mathrm{cum}}$.

After calculating the unweighted $\mathrm{SEL}_{\mathrm{cum}}$ as described above for each 1/3-octave band, the relevant auditory frequency weightings of Section 1.15 are applied and a weighted broadband value $\mathrm{SEL}_{\mathrm{cum,xx}}$ is calculated.

4.7.2. $\mathrm{SEL}_{\mathrm{cum}}$ approach based on fine-resolution sound field

If the sound field of $\mathrm{SEL}_{\mathrm{ss}}$ is provided in a vertical plane 2D grid along a transect, $\mathrm{SEL}_{\mathrm{cum}}$ may be calculated directly from this without use of curve fitting. It is assumed that $\mathrm{SEL}_{\mathrm{ss}}$ is available for all relevant 1/3-octave bands in every grid-point.

Often, the spatial resolution of a numerical model is in the order of metres or decimeters. This fine-resolution grid may, as follows, be used analogously to the curve-fit based approach of Section 4.7.1, with the introduction of Max-Over-Depth, MOD (see definition in Section 1.9).

Preferably, all available grid-points may be used for $\mathrm{SEL}_{\mathrm{cum}}$. Alternatively, a smaller set of evaluation points using this approach shall be separated by maximum 20 m in the horizontal plane. Similarly, in vertical direction the points distributed across the water column shall be separated by maximum 1 m.

- First, all 1/3-octave band values of all evaluation points (i.e. selected grid-points as mentioned above) are frequency weighted according to Section 1.15. For each point, the broadband frequency weighted $\mathrm{SEL}_{\mathrm{ss,xx}}$ is calculated.
- Next, the depth dependence is removed by evaluating MOD for each range step throughout the length of the transect.

The animal receptor is assumed to flee at constant speed v_f [m/s]. At time t_i [s] corresponding to the i'th hammer strike, the receiver is at distance $r_i = r_0 + v_f \cdot t_i$ [m] from the source. For values of fleeing speed v_f, see Table 5.

After these preceding steps, $\mathrm{SEL}_{\mathrm{cum,xx}}$ is evaluated over the entire piling sequence as:

$$L_{E,cum,xx} = 10 \cdot \log_{10} \sum_{i=1}^{N} 10^{\frac{\mathrm{SEL}_{ss,xx}(r_i)}{10}} \, dB$$

Note that until this point, $\mathrm{SEL}_{ss,xx}$ is defined for discrete values of r, and one must provide a scheme for evaluating $\mathrm{SEL}_{ss,xx}$ for the required values of r_i, e.g. by linear interpolation. The applied method must be described.

All hammer strikes of the hammer protocol within a maximum of 24 hours shall be included in SEL_{cum}.

4.8. Vibratory driving: Prognosis of SEL_{cum}

Analogous with impact driving, SEL_{cum} for vibratory driving may be calculated either using a fine-resolution sound field or empirical data. In the following it is assumed that the vibrator operates at constant driving force amplitude throughout the installation of a pile. Alternatively, the method may account for time-varying amplitude, in which case the numerical implementation must be described in detail.

4.8.1. Vibratory driving: SEL_{cum} prognosis based on N_{PL} curve fit

Due to issues related to acoustic interference patterns at low frequencies, the method of this section is not adequate for use with the LF auditory group.

Let step-size s [m] be the horizontal spacing between selected evaluation points, with s≤ 20 m. For a fleeing receptor at constant speed v_f [m/s], this leads to a transition time $\Delta t_s = \frac{s}{v_f}$ [s] between two points along the transect.

Let L_s [dB re 1 μPa^{2}m^2] be the sound pressure source level of the vibrator.

At an evaluation point of spatial index x, the receptor at distance r_x [m] from the source receives sound exposure dose E_x [Pa^{2}s] depending on the vibrator source level as well as the propagation loss:

$$E_x = \Delta t_s \cdot E_0 \cdot 10^{\frac{L_S - N_{PL}(r_x)}{10}}$$

In this, the propagation loss N_{PL} [dB re 1 m^2] is approximated as:

$$N_{PL}(r_x) = X \cdot \log_{10} r_x + A \cdot r_x = X \cdot \log_{10}(r_0 + v_f \cdot r_x) + A \cdot (r_0 + v_f \cdot t_x)\ dB$$

Here, for the receptor at evaluation point x, t_x [s] is the time after onset of the piling sequence, and r_x [m] is the distance of the receptor at time t_x. Values of fleeing speed v_f are given in Table 1Table 5.

Integrating along the transect and over the duration of the installation sequence with a maximum of 24 h, the cumulative SEL becomes:

$$L_{E,cum} = 10 \cdot \log_{10} \sum_{x=1}^{M} \Delta t_s \cdot 10^{\frac{L_{S,max} - X \cdot \log_{10}(r_0 + v_f \cdot t_x) - A \cdot (r_0 + v_f \cdot t_x)}{10}} dB$$

Here, M is the number of evaluation points along the transect.

After calculating the unweighted $\mathrm{SEL}_{\mathrm{cum}}$ as described above for each 1/3-octave band, the relevant auditory frequency weightings of Section 1.15 are applied and a weighted broadband value $\mathrm{SEL}_{\mathrm{cum,xx}}$ is calculated for each auditory group.

4.8.2. Vibratory driving: $\mathrm{SEL}_{\mathrm{cum}}$ prognosis based on fine-resolution sound field

If the sound field of SPL is provided in a vertical plane 2D grid along a transect, $\mathrm{SEL}_{\mathrm{cum}}$ may be calculated directly from this without use of curve fitting. It is assumed that SPL is available for all relevant 1/3-octave bands in every grid-point.

Most often, the spatial resolution of a numerical model is in the order of metres or decimeters. This spatial-wise fine-resolution grid may, as follows, be used analogously to the curve-fit based approach of Section 4.7.1, with the introduction of Max-Over-Depth, MOD (see definition in Section 1.9).

Preferably, all available grid-points may be used for $\mathrm{SEL}_{\mathrm{cum}}$. Alternatively, evaluation points using this approach shall be separated by maximum 20 m in the horizontal plane. Similarly, in vertical direction the evaluation points across the water column shall be separated by maximum 1 m.

Let step-size s [m] be the horizontal spacing between selected evaluation points, with s≤ 20 m. For a receptor fleeing at constant speed v_f [m/s], this leads to a transition time $\Delta t_s = \frac{s}{v_f}$ [s] between two points along the transect.

- First, all 1/3-octave band values of all evaluation points (i.e. selected grid-points as mentioned above) are frequency weighted according to Section 1.15. For each point, the broadband frequency weighted $L_{\mathrm{p,rms,xx}}$ is calculated.
- Next, the depth dependence is removed by evaluating MOD for each range step throughout the length of the transect.

Assume now an animal receptor fleeing at constant speed v_f [m/s]. The receptor reaches an evaluation point of index x at time t_x [s] after piling onset, corresponding to distance $r_x = r_0 + v_f \cdot t_x$ [m] from the source. For values of initial distance r_0 and fleeing speed v_f, see Table 5.

After these preceding steps, $\mathrm{SEL}_{\mathrm{cum,xx}}$ is evaluated over the entire piling sequence as:

$$L_{E,cum,xx} = 10 \cdot \log_{10} \sum_{x=1}^{M} \Delta t_s \cdot 10^{\frac{L_{p,rms,xx}(r_x)}{10}} \, dB$$

Here, M is the number of evaluation points along the transect. All installation time taking place within a maximum of 24 hours shall be included in $\mathrm{SEL}_{\mathrm{cum}}$.

4.9. Installation inactivity and multi-pile foundations

It is assumed for the calculations that the receptor animal keeps fleeing as long as the noise continues. After a period of 5 minutes, i.e. 300 s, without noise, it is assumed the animal remains stationary. Once the noise starts again, the animal flees onward from the stationary position.

This approach applies also to foundation types comprising multiple piles, such as jackets or tripods. For these, the installation sequence commonly involves periods during which the hammer is moved from one pile to another. In this case, the acoustic criteria of Section 2 apply to the foundation, including any number of driven piles for this foundation. Hence, $\mathrm{SEL}_{\mathrm{cum}}$ shall include all piles related to the foundation, and an inactivity limit of 5 minutes shall be accounted for as described above.

As described in Section 2, evaluation of $\mathrm{SEL}_{\mathrm{cum}}$ is based on a 24 hour time window.

4.10. Prognosis uncertainties

A discussion must be provided for identifying the main sources of uncertainties in the prognosis model and the expected confidence intervals on input parameters. For background information, literature examples with in-depth discussions of input parameters and model assumptions are found in [16], [17], and [18].

Preferably, an estimate shall be made of the expected uncertainty for the Prognosis.

If available, reference must be made to previous validation of the applied Prognosis approach against real-world measurements.

4.11. Numerical example

Consider a simplified example of impact pile driving according to the following input data:

- Source Level $L_{E,S}$ is 215 dB with the 1/3-octave band spectrum shown in Table 8
- The hammer energy increases in the following way: 400 blows at 15%, 1400 blows at 20% 1400 blows at 40%, 1400 blows at 60%, 1400 blows at 80% and 1200 blows at 100% (a total of 7200 blows and 6 h installation time with a uniform ramming frequency of 1 strike per 2 s
- The Propagation Loss $N_{PL,E}(r) = X \cdot \log10(r) + A \cdot r$ is given per 1/3-octave band in Table 8

- Fleeing speed is 1.5 m/s
- The transect is assumed to not reach shore at any distance from the source
- An ADD is applied that corresponds to an r_{safe} of 1,100 m

For simplicity, only the frequency range 63 to 50,000 Hz is considered in this example, and only the LF and PCW auditory groups. The Propagation Loss data of Table 8 are a smoothened version of measurement data using an airgun as sound source. These data are intended for the numerical example only and may not be used for planning related purposes.

Reference case

For the unmitigated case, the resulting SEL$_{cum}$ is shown in Figure 4 as a function of initial distance r_0 for the two auditory groups. The plot shows the PCW animal starting at any initial distance will be exposed to an SEL$_{cum}$ that is less than the corresponding PTS threshold value of 185 dB re 1 μPa^{2}s. This is contrasted by the LF animal, which is seen to exceed its PTS threshold for any initial distance within the Distance-To-Threshold r_{PTS} of 27,422 m.

Inspecting the scenario at maximum permitted initial distance r_{safe}=1.1 km, the SEL$_{cum}$ with LF weighting is 196.5 dB re1 μPa^{2}s. This is an excess of 13.5 dB compared to the PTS threshold. With PCW weighting, the SEL$_{cum}$ at the same distance is 175.2 dB, representing a margin of 9.8 dB compared to the threshold value.

1/3-octave band frequency [Hz]	Source Level	Propagation Loss coefficients	
	SL$_E$ [dB re 1μPa^{2}m^{2}s]	X [-]	A [m^{-1}]
63	202.3	11.2	0.00021
80	204.8	11.2	0.00021
100	207.0	11.2	0.00022
125	208.7	11.3	0.00022
160	207.8	12.1	0.00021
200	205.9	12.3	0.00022
250	202.6	13.2	0.00032
315	200.1	13.3	0.00038
400	197.4	13.6	0.0004
500	195.5	15.1	0.00041
630	193.8	19.0	0.00042
800	192.0	21.0	0.00041
1000	189.5	24.0	0.0004
1250	187.3	23.1	0.00031
1600	185.2	22.0	0.00025
2000	183.4	20.7	0.00019
2500	181.7	20.8	0.00015

3150	179.5	19.6	0.00014
4000	177.4	18.7	0.00012
5000	175.3	17.1	0.00011
6300	173.6	16.7	0.00011
8000	171.6	16.5	0.0001
10000	169.4	15.7	0.0001
12500	167.5	14.3	0.0001
16000	165.3	12.9	0.0001
20000	163.3	11.8	0.0001
25000	161.3	10.6	0.0001
31500	159.3	10.2	0.0001
40000	157.3	10.1	0.0001
50000	155.3	10.1	0.0001
Total	**215.0**	-	-

Table 8: Source Level and Propagation Loss coefficients per 1/3-octave bands for calculation example. These data are intended for the numerical example only and may not be used for planning related purposes.

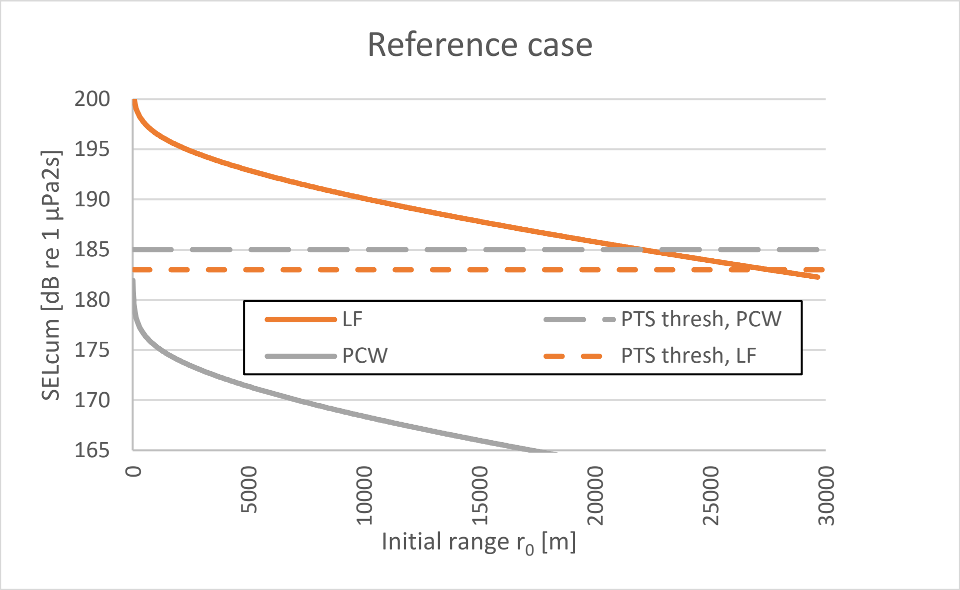

Figure 4: Reference case: Calculated SEL$_{cum}$ as a function of initial distance r_0 for LF and PCW auditory groups. Corresponding PTS thresholds are indicated by dashed lines.

Planned construction case

Next, the prognosis is done again with the assumption of an idealized noise reduction technique, which attenuates the source level equally in all 1/3-octave bands by 15 dB. In this scenario Figure 5 shows that as before, the PCW animal meets the PTS criteria by a great margin for any initial range. Also, the LF animal meets the PTS criteria for initial ranges greater than r_{PTS}=360 m, which fulfils the requirement of a maximum permitted r_{PTS} being less than

r_{safe}=1,100 m. At the same time, since r_{PTS} is greater than 200 m, the general use of an ADD is permitted. A prognosis for the specifically intended ADD device should be carried out as a final step.

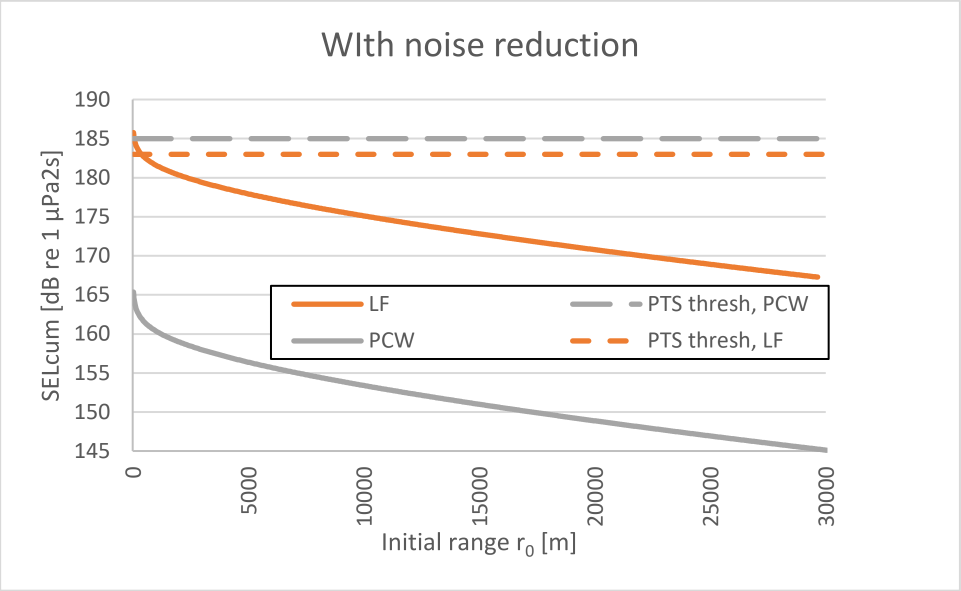

Figure 5: Planned construction scenario: Calculated SEL_{cum} as a function of initial distance r_0 for LF and PCW auditory groups. Corresponding PTS thresholds are indicated by dashed lines.

5. Verification measurements

On-site measurements of underwater sound shall be taken with two purposes:

- Verification of propagation model used in the Prognosis
- Demonstration of compliance with acoustic criteria

Equipment requirements are given in Appendix A.

5.1. Verification of propagation model

To demonstrate the validity of the Prognosis the bidder is required to perform propagation verification measurements as required in the Conditions.

To reduce the risk of relating compliance measurements of Section 5.3 to a Prognosis model that does not represent the actual acoustic environment, the Concession Holder may at an earlier time perform transect measurements using an artificial underwater sound source, e.g. an airgun. The propagation verification is done in terms of 1/3 octave band transmission loss (TL). An overview of the procedure is shown in Figure 6. Due to issues related to acoustic interference patterns at low frequencies, the method of this section shall only be applied above 400 Hz.

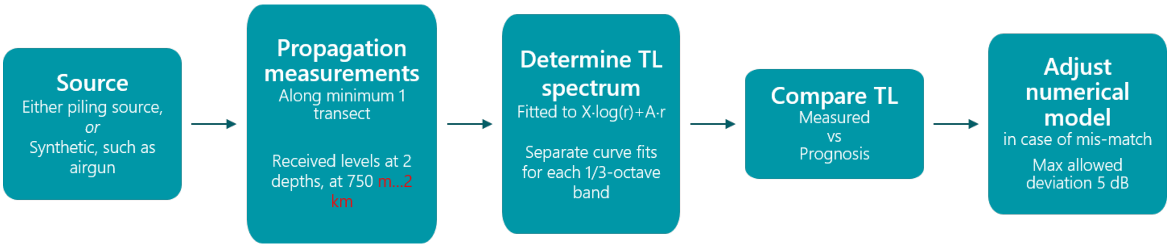

Figure 6: Overview flow diagram for propagation model verification.

For an impulsive sound source, either artificial or from impact piling, the measurement metric is SEL_{ss}. For a continuous sound source, either artificial or from vibratory driving, the metric is SPL, based on 60 s averaging time. The measurement-based set of TL per 1/3-octave band is determined following the method described previously in Section 4.5.4.1. Receiver depths for the measurement-based TL shall correspond to those of the Prognosis-based TL (Section 4.6).

A minimum of one transect shall be investigated. This shall be selected from the Prognosis as the one expected to provide the highest SEL_{cum}. If different transects are identified for different auditory groups, it shall be justified which one was selected for the verification measurements.

The transect measurements shall be performed by short duration hydrophone deployment at a number of different distances.

The transect propagation measurements shall:

- Report the agreement between the sound propagation model and the transect validation measurements.
- Include reference data recorded at 750 m distance, using this as a reference distance.
- If performed prior to piling:
    - A minimum set of receiver ranges are: 750 m, 1,000 m, 1,500 m, and 2,000 m. It is recommended to furthermore include receivers at 3 km, and between 5 and 10 km.
- If performed during piling:
    - A minimum set of receiver ranges are: 750 m, 1,000 m, 1,500 m, 2,000 m, and 3,000 m. It is recommended to furthermore include a receiver between 5 and 10 km.
- Measured perpendicular to a straight line originating from the source, the receiver positions shall not deviate from that straight line by more than 5% of the horizontal distance from the source.
- The actual horizontal receiver distances from the source shall be determined with a measurement uncertainty of 5% of the target distances.
- For each receiver position, measurements must be taken at two hydrophone depths: 50% and 75% water depth (measured from sea surface). The receiver depths shall be decided from the shallowest reference position. As an example, if the shallowest position has water depth of 32 m the TL curve fits shall be made at 16 and 24 m depth. Vertical receiver positions shall be determined with an uncertainty of 5% or better.
- During the measurements at sea, the water sound speed profile across the water column must be measured at least once per 4 hours of acoustic measurement activity.
- Report details of calculation of level correction due to distance, or due to variation in source level properties.

Measured metrics that exceed or are equal to the background noise (Section 5.2) shall be corrected according to Section 1.11.

The measurements shall be used to determine a transmission loss, based on curve fit to the expression $\Delta L_{TL}=X_{TL}\cdot\log_{10}(r)+A_{TL}(r)$. Here, X_{TL} is a positive constant, and A_{TL} is positive or negative. It is noted that the curve-fitting often involves a non-zero offset, specific to the sound source. However, only X_{TL} and A_{TL} are used. Separate curve fits shall be made for each unweighted 1/3-octave band.

The quality of each fit shall be inspected. It must be expected that limitations will arise for high-kHz frequencies and long distances.

Direct comparison shall be made of measurement-based versus Prognosis-based transmission loss. For each 1/3-octave band, and for a distance of 3 km, these two versions of transmission loss shall not deviate from each other by more than ±5 dB. The deviation must not be single-sided. For larger deviations, the verification will be considered to have failed. In that case the Concession Holder will have to revise the model in order to fit the verification measurements.

The Concession Holder shall report the verification to the Danish Energy Agency including a discussion of the agreement between prognosticated and measured data. In case of disagreement between prognosticated and verification measurements it is required that the report can be accepted by the Danish Energy Agency before installation can commence or continue.

5.2. Measurement of background noise

Measurements of background noise shall be undertaken when sound from pile driving is not present. This can be either before or after the pile driving or during any significant gaps (more than 1 minute) in the pile driving sequence. It is recommended that any such measurements are performed at one of the locations used for measurement of the pile driving noise, or at a location which is considered representative. The background noise measurements are intended for subsequent correction of measurements taken during installation. Hence, it is preferable for the background noise measurements to include contributions from relevant support vessels.

The hydrophone deployment depth shall be the same as for the measurements during pile installation.

The background noise shall be analysed as root-mean-square sound pressure level (SPL) $L_{p,rms}$ with an averaging time of 60 s. Measurements shall be taken over minimum 10 minutes, and the 60 s blocks need not be contiguous.

The background noise shall be reported as unweighted 1/3-octave band spectra based on:

- Minimum $L_{p,rms}$
- Maximum $L_{p,rms}$
- Median (50% exceedance, L_{50}) $L_{p,rms}$
- Mean and standard deviation of $L_{p,rms}$

Furthermore, unweighted broadband values as well as with auditory weightings of Section 1.15 shall be presented according to the above statistical parameters.

For good quality measurements of background noise, a measurement system with sufficiently low self-noise should be used. Note that it might not be appropriate to use the same hydrophone for the background noise measurements as that used for the measurement of the sound from the pile driving. Advice on this is found in ISO 18406 [1].

5.3. Compliance with acoustic criteria

To demonstrate the validity of the Prognosis the bidder is required to perform compliance verification measurements as required in the Project Conditions with the actual piling activity. If the PTS threshold (see Section 2) is not met, verification measurements shall also be performed at subsequent piles, as required in the Conditions, until the installation methods and noise mitigation measures have been adjusted such that requirements are fulfilled, and this can be demonstrated by the verification measurements. Such correcting actions to comply with the thresholds shall be approved by the Danish Energy Agency.

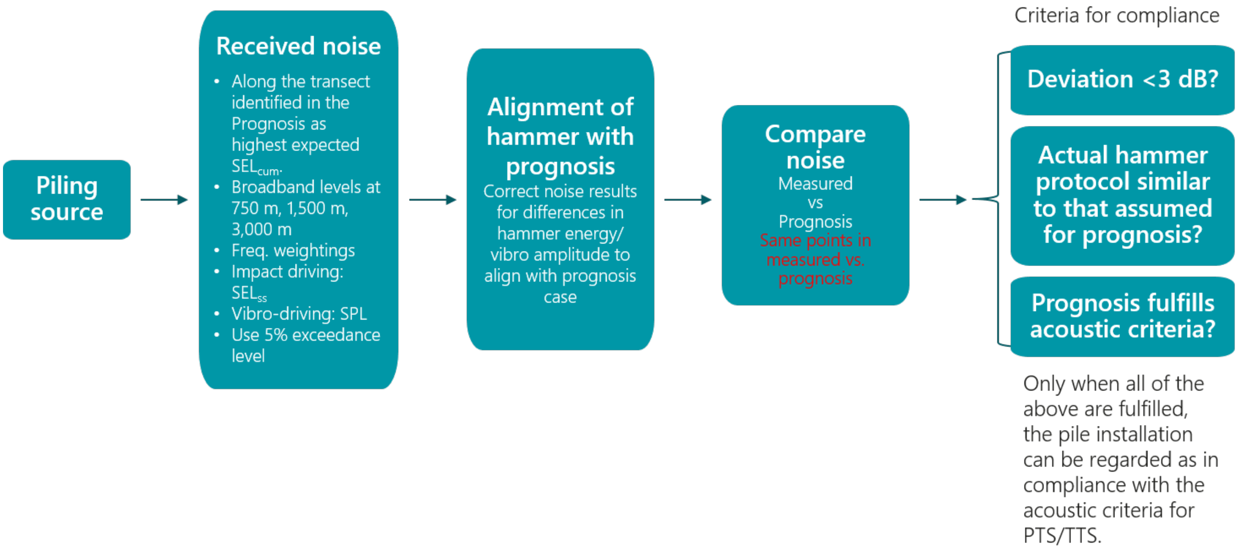

Figure 7: Overview flow diagram for compliance verification.

Measurements shall be taken along minimum one transect identified in the Prognosis as having the highest expected SEL_{cum}. It is recommended to measure along more transects.

Measured metrics exceeding or equal to the background noise (Section 5.2) shall be corrected according to Section 1.11.

Measurements shall be taken along each transect at ranges 750 m, 1500 m, and 3000 m with a tolerance of ±5% of the nominal distance. Actual deployment positions shall be distance-corrected to the nominal ranges using transmission loss data from the Prognosis, such as of the approximate type $\Delta L_{TL}=X_{TL}\cdot\log_{10}(r)+A_{TL}(r)$ dB

The type of distance-correction applied shall be described.

At each range step, the same two hydrophone depths as in the Prognosis shall be used for the measurements. The hydrophones shall be deployed in a transect along a straight line originating at the pile position. Measured perpendicular to a straight line originating from the pile, the receiver positions shall not deviate from that straight line by more than 5% of the horizontal distance from the source.

The relatively shallow water depths relevant for bottom-fixed foundations form a waveguide type of acoustic environment. The resulting sound field can be expected to present regular fringes, or “striations” [19]. A case from a Danish site showed oscillations over distance with a wavelength of around 80 m [16]. On that background, it is recommended to supplement the measurement at 750 m (nominally) with one or more measurement points approximately 40 m closer to the source or further away from the source. This will provide a quantification of the spatial variability and allow the Concession holder not to be dependent on a measurement that is less representative for his Prognosis.

During the entire pile installation sequence, with a maximum of 24 h the following metrics shall be recorded:

- For impact driving: single-strike sound exposure level SEL_{ss}
- For vibratory driving: sound pressure level SPL (as a function of time) averaged over 5 s

The above metric shall be reported as unweighted 1/3-octave band spectra based on:

- Minimum level
- Maximum level
- Median (50% exceedance level L_{50}, which is the level exceeded in 50% of the measurements over the total measuring period)
- Mean and standard deviation
- 5% exceedance level L5, which is the level exceeded in 5% of the measurements over the total measuring period

Furthermore, broadband values unweighted as well as with auditory weightings of Section 1.15 shall be presented according to the above statistical parameters.

For impact hammer energy deviating during the measurement from the corresponding reference hammer energy of the Prognosis, a correction may be made according to the unweighted SEL_{ss} values (derived from [20]):

$$\Delta L_E = 8.3 \cdot \log_{10} \frac{W_1}{W_0}\, dB$$

Here, W_1 [kJ] is the actual hammer energy during measurements, and W_0 [kJ] is the reference hammer energy of the Prognosis. Until further notice, it is suggested to use the same correction for deviations of vibratory driving force. If alternative correction methods are applied, these must be described.

The broadband 5% exceedance levels shall be compared to those of the Prognosis. If these broadband levels deviate from those of the Prognosis by less than 3 dB, the Prognosis and verification measurements can be regarded as verified for SEL_{ss}. Alternatively, the Prognosis must be revised. It must be expected that limitations will arise for high-kHz frequencies and long distances.

For a Prognosis that has been verified for SEL_{ss} as described above, it must furthermore be demonstrated that the assumed hammer driving protocol is in reasonable agreement with that of the actual pile installation. In this case, and if the Prognosis complies with the acoustic criteria of Section 2, the measurements can also be regarded as in compliance.

5.4. Measurement uncertainty

An assessment of the measurement uncertainty related to results of the verification measurements must be presented. Advise for this is given in ISO 18406 [1].

As background information, measurement uncertainty for unweighted SEL_{ss} is often expected as ±3 dB ([16], [21]) although at the time of writing of this Guideline this value is not well documented in the literature.

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7. Appendix A Requirements for measurement recording equipment

Equipment requirements and advise on hydrophone deployment is given in ISO 18406 [1] with the additional comments listed below. Any deviation of the above must be described and justified.

- Measurements shall cover the frequency range 12.5 Hz to 80 kHz
- Preferably, measurements shall cover the range 12.5Hz to 178 kHz
- At least 16 bit resolution is required
- Adequate sensitivity of hydrophone and gain settings of amplifiers to prevent clipping and minimize limitation by self-noise of recorder.

It is recommended to record a calibration signal during the measurement campaign.