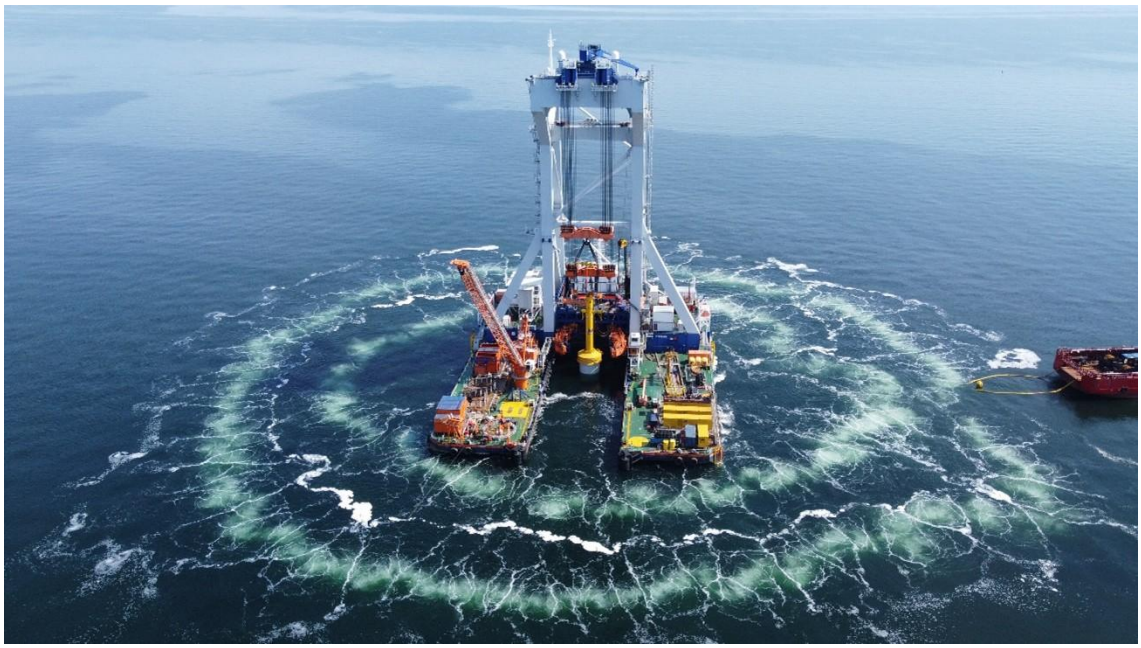
Guideline for underwater noise

Installation of impact or vibratory driven piles

August 2026



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List of abbreviations

ADD	Acoustic Deterrent Device
AUD INJ	Auditory Injury
BT	Beam Tracing
DTT	Distance-to-Threshold
FE	Finite Element
FP	Full Power
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 Auditory Injury (AUD INJ), Temporary Threshold Shift (TTS), and behavioural impact. The acoustic criteria are based on auditory frequency weighting functions as relevant to marine mammal species in Danish waters.

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

Concessionaire 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 animal while it is fleeing from the noise source. The prognosis must include case 1 and 3 below, while case 2 and 4 might be required depending on the installation method.

1. Reference case (required)
2. Mitigated case
3. Interruption ADD case (required)
4. Pre-piling ADD case.

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.

Comments to Summer 2026 version

In this latest edition, the following modifications were implemented:

Auditory Injury (AUD INJ) has been introduced as a replacement for Permanent Threshold Shift (PTS) based on new scientific basis, as outlined in [23]. This change leads to revised frequency weighting functions and acoustic criteria for AUD INJ and for Temporary Threshold Shift (TTS).

Clarified guidance as relates to the use of Acoustic Deterrent Devices (ADD) as a method for pre-piling deterrence.

Revised concept for marine mammal starting distance input, and for marine mammal behaviour during interruptions.

Revised wording for sound propagation measurements, now clearly stating that first-pile propagation measurements are required.

Revised concept for on site measurements and compliance criteria.

Introduction of guidance relating to handling interruptions during pile driving, based on a target of preventing negative impacts on marine mammals.

Comments to Spring 2023 version

In the spring 2023 revision a few modifications were implemented as follows:

To limit the impact of the ADD, a criterion was introduced for maximum distance-to-threshold based on PTS.

For on-site compliance demonstration, the criterion was relaxed to allow for conservative "over-estimation" at the time of the Prognosis.

In addition, several typographical errors were corrected throughout the document.

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. AUD INJ/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 of an ADD is generally prohibited during the construction sequence with exceptions for special cases.

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.

Section 6 addresses protective measures for marine mammals related to interruptions during pile driving.

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 considers 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 an update of the Danish Guideline in 2022, new scientific evidence extracted by DCE in a series of technical reviews [6][7][8] served as background reports for the revision. The technical reviews from DCE and the overall update of the Guideline were discussed in a working group before being published. Modifications for the Guideline were introduced in the Spring 2023, by the same working group.

The continued scientific advancements, and the real-world application of the 2023 version of this Guideline, prompted a new working group to undertake a revision of this Guideline in 2026. This version includes changes to several key aspects of the Guideline, and includes updated acoustic criteria based on a technical review of new scientific literature [23].

The 2026 revision was undertaken by:

- Senior Specialist Mark Aarup Mikaelsen, NIRAS
- Chief Advisor Søren Keller, Danish Energy Agency
- Chief Advisor Alf Skovgaard, Danish Energy Agency
- Advisor Jens Rasmus Meilbye Pedersen, Danish Energy Agency

The 2022 working group consisted 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 significant 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 2026 Guideline replaces all former versions of this Guideline and the former 2016 Guideline with immediate effect.

Scope of the work

For installation of offshore wind turbine foundations, the Concessionaire 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 Concessionaire 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 Concessionaire 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 Auditory Injury (AUD INJ) 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 Concessionaire 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 key 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 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 $p_{ms}\ [Pa^2]$:

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

The RMS pressure $p_{rms}\ [Pa]$ is the root of p_{ms}.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 $p_0 = 1\ \mu Pa$.

To evaluate 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 µPa²s.

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_{ss}, symbol: $L_{E,p}$) 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 $E_0 = 1 \; \mu Pa^2 s$.

The calculation of SEL_{cum} for a specific installation depends on the driver type (impact or vibratory) and on the calculation method (propagation loss curve fit or fine-resolution sound field). Please refer to:

- section 4.7.1 for impact driving, and SEL_{cum} calculation from propagation loss curve fit,
- section 4.7.2 for impact driving, and SEL_{cum} calculation from fine resolution sound field,
- section 4.8.1 for vibratory driving, and SEL_{cum} calculation from propagation loss curve fit, section 4.8.2 for vibratory driving, and SEL_{cum} calculation from fine resolution sound field.

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 type-I, or impulsive type of sound source (see definitions in Sect. 1.13), the sound exposure source level with symbol $L_{S,E}$ $[dB\ re\ 1\ \mu Pa^2m^2s]$ 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 $1\ \mu Pa^2s@1m$.

Similarly, for a continuous source the source level L_S $[dB\ re\ 1\ \mu Pa^2m^2]$ is the time-integrated squared sound pressure level at 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 $1\ \mu Pa \cdot m$. In the literature, this metric is sometimes cited as source level with reference value of $1\ \mu Pa@1m$. 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:

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

The reference value for $N_{PL,E}$ is 1 m^2.

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

The reference value is 1 m when using the sound pressure level definition of Sect. 1.2, based on $20 \cdot Log(p/p_0)$. Alternatively, the reference value is 1 m^2 when using the equivalent power quantity-based definition $10 \cdot Log(p^2/p_0^2)$ of ISO 18405 [2].

1.8. Transmission loss ΔL_{TL}

With symbol DL_{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. 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_{05} is the level which is exceeded in 5% of the observations. Similarly, L_{50} is the level which is exceeded in 50% of the observations (also referred to as the Median).

1.11. Distance-To-Threshold

Typically evaluated from a Max-Over-Depth parameter (Section 1.9), or a justified exceedance level over depth (section 1.10), 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.

DTT for a specific threshold is referenced $r_{threshold}$. For Auditory Injury (AUD INJ) and Temporary Threshold Shift (TTS) thresholds, this is calculated by iteration over the animal starting distance r_0 in the relevant equation for SEL_{cum} (see section 1.5) until SEL_{cum} is equal to, or less than the respective threshold value. For behaviour disturbance thresholds, this is calculated by determining the distance beyond which SPL_{125ms} at maximum hammer energy no longer exceeds the threshold criteria.

1.12. 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]). The background noise shall be measured within 24 hours before or after the pile installation noise.

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.

1.13. 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. Hammer energy profile

For the purpose of this Guideline, the hammer energy profile is defined as the prognosed hammer energy applied per strike (impact piling) or per time interval/operating level (vibratory piling) as a function of installation progress (time, penetration depth, or pile strike count). A theoretical hammer energy profile consisting only of strikes at 100% hammer energy is referred to as the Full Power (FP) hammer energy profile.

1.15. 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].

1.16. 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 [24], 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	f_1	f_2	C
LF	0.99	5	0.168 kHz	26.6 kHz	0.12 dB
HF	1.55	5	1.73 kHz	129 kHz	0.32 dB
VHF	2.23	5	5.93 kHz	186 kHz	0.91 dB
PCW	1.63	5	0.81 kHz	68.3 kHz	0.29 dB

Table 1: Parameters for auditory weighting functions of hearing groups relevant to Danish waters. Data from [24].

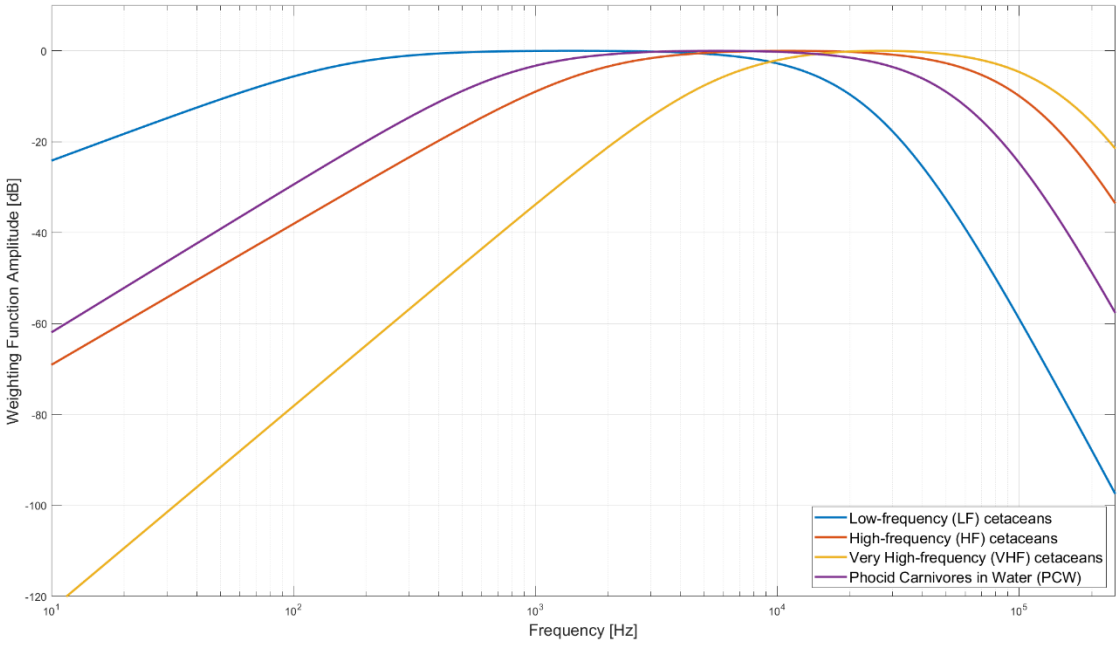


Figure 1: Frequency weighting functions proposed by [24] for auditory groups relevant to Danish waters.

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, f_1 and f_2 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 [24] 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 – 30,000 Hz
HF	150 – 160,000 Hz
VHF	200 – 165,000 Hz
PCW	40 – 90,000 Hz

Table 2: Practical, indicative frequency ranges for hearing of auditory groups relevant to Danish waters [24].

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 Auditory Injury (AUD INJ) and Temporary Threshold Shift (TTS) [24]. 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 AUD INJ and TTS thresholds were derived from [24].

In the tables, AUD INJ and TTS threshold values are given as SEL_{cum} with the respective auditory weighting functions (Section 1.16). 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 from the onset of pile installation activity. Behavioural disturbance shall be evaluated for a single pile strike at maximum hammer energy for impact driving or at maximum driving force for vibratory driving.

For the purposes of this Guideline, the term "project-relevant hearing groups" refers to the subset of marine mammal auditory groups for which exposure is considered plausible given the project's acoustic characteristics, geographic setting, and temporal extent. It is the responsibility of the Concessionaire to determine which and how many of the species listed in Table 3 and Table 4 shall be considered. The relevant hearing groups shall be identified at the outset of the assessment and justified based on source frequency spectrum, sound levels, and species occurrence in the concession area. As a starting point, the overview in [6] may be consulted for background.

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

- Animal having starting position (r_0) of, or greater than, 200 m from the installation, and increasing its distance to the source as instructed in section 2.1.
- During the installation of any single foundation. In practice, the Concessionaire 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**		
			AUD INJ	**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	159	144	103
White-beaked dolphin	Hvidnæse	HF	193	178	-
Pilot whale	Grindehval	HF	193	178	-
Minke whale	Vågehval	LF	183	168	-
Harbour seal	Spættet sæl	PCW	183	168	-
Grey seal	Gråsæl	PCW	183	168	-

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 µPa²s and SPL in dB re 1 µPa. Only thresholds for I-type sounds are shown.

Other sounds					
Species (English)	**Species (Danish)**	**Weighting**	**Threshold type**		
			AUD INJ	**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	181	161	*)103
White-beaked dolphin	Hvidnæse	HF	201	181	-
Pilot whale	Grindehval	HF	201	181	-
Minke whale	Vågehval	LF	197	177	-
Harbour seal	Spættet sæl	PCW	195	175	-
Grey seal	Gråsæl	PCW	195	175	-

*Table 4: Species in Danish waters with corresponding auditory groups and respective acoustic thresholds stated as SEL_{cum} in dB re 1 µPa²s 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.*

2.1. Animal fleeing behaviour

For the purpose of this Guideline, animals are assumed to flee radially away from the noise source at a constant speed v_f $[\frac{m}{s}]$, from an initial starting distance r_0 $[m]$, from time t_0 $[s]$ representing the onset of pile installation. 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 on a scientific or empirical basis 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.

For calculation of Distance-To-Threshold (DTT, see section 1.11) for AUD INJ and TTS SEL_{cum} threshold criteria, the SEL is numerically cumulated as the receptor animal moves away from the noise source along the transect and receives new partial doses for each range step. Where this approach results in the animal reaching the shoreline prior to completion of the installation activity, the cumulative exposure shall be calculated by assuming continued exposure to the final received SEL corresponding to the position before reaching the shoreline for the remainder of the installation period. Given the uncertainty associated with marine mammal movement and site-specific behavioural responses, this assumption represents a precautionary approach that avoids underestimation of cumulative exposure. Alternative concepts for fleeing behaviour upon reaching a shoreline may be applied in the calculations. In this case the concept must be justified.

It is furthermore assumed for the calculations that the receptor animal keeps fleeing as long as the noise source is active. The receptor animal is assumed stationary during interruptions whatever the cause, resuming fleeing on resumption of the activity. A receptor animal with fleeing speed v_f $\left[\frac{m}{s}\right]$ from an initial starting position of r_0 $[m]$, after an active pile driving duration, t_{active} $[s]$, and an interruption duration, t_{int} $[s]$, the receptor animal distance at restart is:

$$r_{restart} = r_0 + v_f \cdot (t_{active})\ [m]$$

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 Table 3, Table 4 apply to the foundation, including any number of driven piles for this foundation. Hence, SEL_{cum} shall include all piles related to the foundation, and inactivity between driving of individual piles shall be accounted for as described above, however limited to a 24-hour time window.

3. Acoustic Deterrent Device

In the context of offshore piling, Acoustic Deterrent Devices and Acoustic Startle Devices (collectively referred to as “ADDs”) is a group of devices designed specifically for deterring marine animals by emitting underwater sound. An ADD is intended to produce non-injuring discomfort to the marine mammals and cause them to move away from the noise source. Ideally, it deters the marine mammals from potential injury zones [9].

3.1. Use of an ADD as pre-piling deterrence

The use of an ADD as pre-piling deterrence is generally prohibited. In special cases where it is not possible to ensure $r_{AUDINJ,xx} \leq 200\ m$ for one or more relevant hearing groups (xx), use of an ADD to deter marine mammals prior to the pile driving may be permitted, upon consultation with the DEA on the basis of a mitigated prognosis, see Figure 2. If permitted, the applicant must prepare an ADD prognosis demonstrating the effect of the ADD.

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, Ray Tracing 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 Concessionaire to estimate the environmental impact using the given sound source and propagation properties and calculate the cumulative SEL experienced by a receptor animal while it is fleeing away from the noise source.

4.1.1. Required Prognosis scenarios

As illustrated in the flow diagram of Figure 2, the prognosis must include case 1 and 3 below, while case 2 and 4 might be required depending on the installation method.

1. Reference case (required)
2. Mitigated case
3. Interruption ADD case (required)
4. Pre-piling ADD case

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

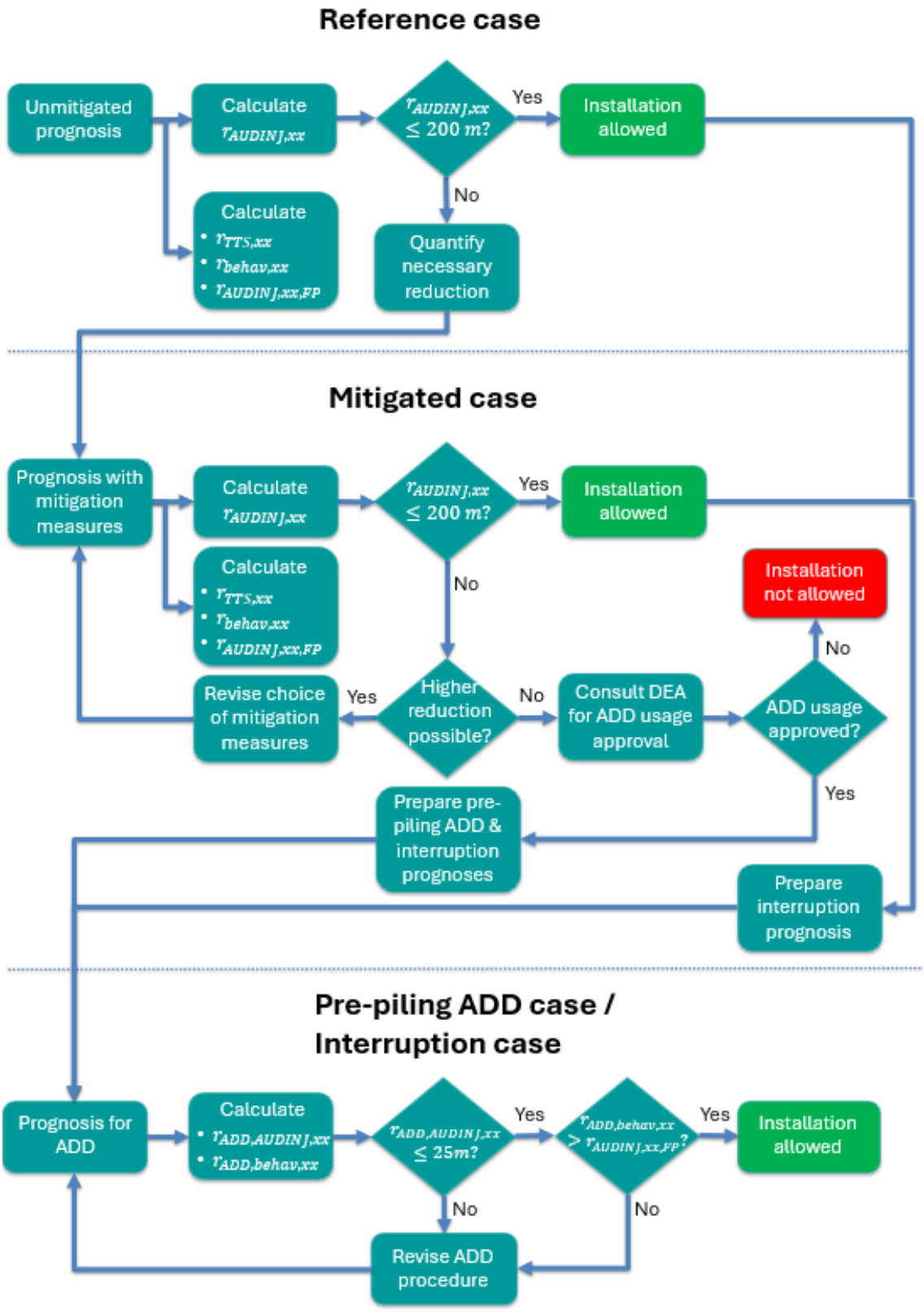


Figure 2: Overview flow diagram for prognosis scenarios.

Reference Case

This case represents the unmitigated scenario of the piling operation, assuming the piling to be performed without noise reduction techniques (Section 4.1.3), and with the planned hammer energy profile (see section 1.14).

The AUD INJ Distance-to-Threshold (DTT, see Section 1.11) ($r_{AUDINJ,xx}$), with appropriate frequency weightings (xx) shall be determined through iteration over the animal starting distance r_0 for the relevant SEL_{cum} equation (see section 1.5) for the project relevant auditory groups (Section 2). If $r_{AUDINJ,xx} \leq 200\ m$ for all project relevant auditory groups, installation is allowed, and an interruption prognosis must be prepared.

If $r_{AUDINJ,xx} > 200\ m$ for any project relevant auditory group, noise reduction is quantified by calculating the SEL_{cum} based on a starting distance $r_0 = 200\ m$, and compared to the AUD INJ threshold criteria for all project relevant auditory groups. The outcome is a quantification of minimum required noise reduction. It is noted that as point of departure, the same hammer energy profile shall be assumed for both Reference Case and Mitigated Case, if mitigation should be required.

Similarly, the DTT of TTS ($r_{TTS,xx}$) and of the $SPL_{125\ ms}$ behavioural criteria ($r_{behav,xx}$) stated in Table 3 and Table 4 shall be determined.

In addition to the planned hammer energy profile, the AUD INJ DTT must be calculated assuming Full Power (FP) hammer energy applied throughout installation, resulting in $r_{AUDINJ,xx,FP}$, to represent the potential impact in case of a late-stage interruption restart at maximum hammer energy.

Mitigated Case

If noise reduction is required, a separate Prognosis must be performed describing the installation scenario including suitable mitigation measures. The Mitigated Case assumes the piling operation to be the only active noise source in the Prognosis model.

The procedure for calculation of AUD INJ DTT follows the same procedure as outlined for the Reference Case, however, includes the proposed mitigation. If the proposed mitigation measures lead to $r_{AUDINJ,xx} \leq 200\ m$ for all project relevant hearing groups, installation is allowed, and an interruption prognosis must be prepared.

In cases where all reasonable mitigation measures have been applied and $r_{AUDINJ,xx} \leq 200\ m$ remains unmet for one or more project-relevant hearing groups, the DEA must be consulted, to determine the use of ADD. If the DEA permits the use of ADD, the Concessionaire must

undertake an ADD specific prognosis for pre-piling deterrence. As seen below, the pre-piling ADD case and Interruption ADD case are similar in all aspects.

Similarly, the DTT of TTS ($r_{TTS,xx}$) and of the $SPL_{125\ ms}$ behavioural criteria ($r_{behav,xx}$) stated in Table 4 shall be determined. The Full Power (FP) hammer energy profile AUD INJ DTT, $r_{AUDINJ,xx,FP}$ must also be calculated to represent the potential impact in case of a late-stage interruption restart at maximum hammer energy.

Pre-piling ADD Case / Interruption ADD Case

The pre-piling ADD case and Interruption ADD case are similar in all aspects, however, are triggered by different mechanisms in the flow diagram. The pre-piling ADD case is relevant where the mitigated prognosis shows that $r_{AUDINJ,xx} \leq 200\ m$ can not be met for one or more project relevant hearing groups, and the DEA has permitted the use of pre-piling ADD as deterrence. The interruption ADD case however must always be calculated for any valid installation, to represent the deterrence of marine mammals after pile driving inactivity where the planned hammer energy profile can not be reapplied in full at restart.

For both cases, the specific ADD is the only active noise source to be included in the Prognosis (i.e. no piling source). Here, device specific source level (as frequency spectrum) e.g. from vendor data shall be used as input to the Prognosis. An evaluation against project relevant hearing groups shall be performed:

DTT shall be determined for the AUD INJ criteria of Table 3 and Table 4, resulting in $r_{ADD,AUDINJ,xx}$. Similarly, behavioural criteria of Table 3 and Table 4 shall be determined, which is $r_{ADD,behav,xx}$. The appropriate Full Power hammer energy profile AUD INJ DTT, $r_{AUDINJ,xx,FP}$ from either the reference, or the mitigated case is also used as input.

If both conditions: $r_{ADD,behav,xx} > r_{AUDINJ,xx,FP}$ and $r_{ADD,AUDINJ,xx} \leq 25m$ for all project relevant hearing groups is fulfilled, the ADD is permitted. A soft-start/ramp-up procedure for the ADD may be needed to achieve this.

It is noted that this calculation only applies for species where a behavioural disturbance criterion is currently supported, see section 2.

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 hammer energy profiles 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 Concessionaire shall propose noise reduction measures, which ensures compliance with the relevant AUD INJ thresholds of Section 2.

The Concessionaire 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.
- 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 minor 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 Concessionaire 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 AUD INJ 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, Concessionaire may choose a transect length sufficiently long to address the behavioural disturbance.

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 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	15 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 explicitly implemented, assumptions regarding the non-modelled frequency range shall be presented and justified in the Prognosis report.

As described in Section 1.15, 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 hammer energy profile.
  - For impact piling, this is hammer energy, e.g. as presented in the simplified hammer energy profile example of Table 7. This can be thought of as a proposed driving "history" and may be provided both as tables and 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 energy profile 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 described here 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 1.12.

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} [-]and A_{TL} [m^{-1}] are positive constants, 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 AUD INJ 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 $SEL_{ss,xx}$, SPL_{xx} and $SPL_{125\ ms,xx}$ 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 (L_{05}).

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} [-]and A_{TL} [m^{-1}] are positive constants, 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 hearing 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

For the receptor animal 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, $L_{E,cum}\ [dB\ re\ 1\ \mu Pa^2 s]$ becomes:

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

Here, $E_0 = 1\ \mu Pa^2 s$ is the reference value for sound exposure.

At time t_i after piling onset, the receptor animal is at range $r_i = r_0 + v_f \cdot t_i\ [m]$, based on fleeing behaviour defined in section 2.1. For calculation of minimum necessary noise reduction for all relevant species, the value of r_0 is defined in section 2.

For calculation of Distance-To-Threshold (DTT) for AUD INJ and TTS for project relevant hearing groups, an iterative procedure over r_0 is performed until SEL_{cum} is equal to the respective species-specific threshold criteria. The process is illustrated schematically in Figure 3 for the case of AUD INJ DTT.

Behaviour Disturbance DTT must be determined as the distance r where $SPL_{125ms,xx}$, which is estimated from SEL_{ss}, see Section 1.2, intersects the threshold criterion, see Table 3 and Table 4.

In the following, all metrics shall be calculated per 1/3-octave frequency band with appropriate frequency weighting according to Section 1.16. Hence, in $SEL_{cum,xx}$ the subscript xx refers to the auditory weightings LF, HF, VHF, or PCW in the following.

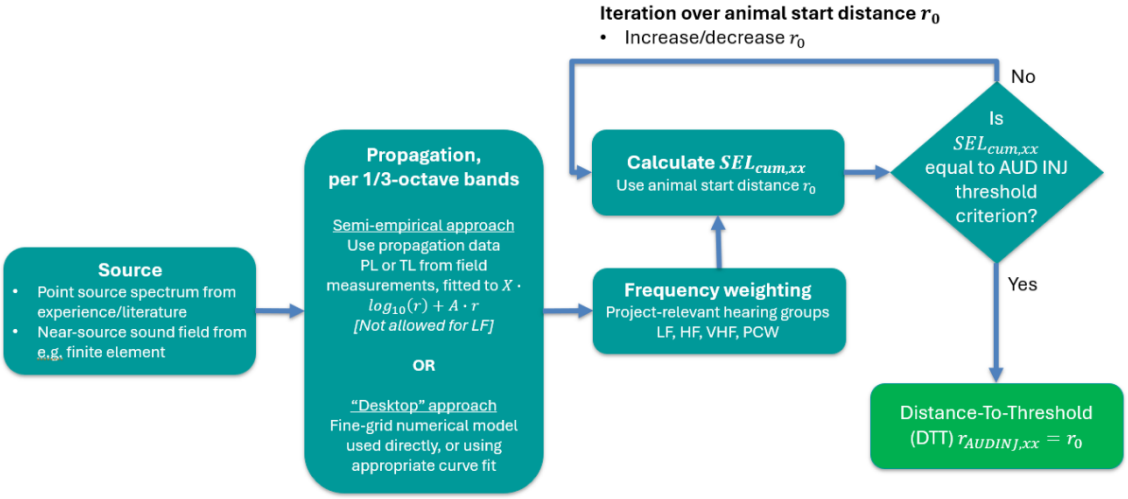


Figure 3: Overview flow diagram showing iterative procedure for Distance-To-Threshold.

4.7.1. SEL_{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 hearing group.

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

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 $L_{S,E}$ $[dB\ re\ 1\ \mu Pa^2m^2s]$, the received single-strike SEL at any range r $[m]$ is calculated as:

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

Let the unweighted source level $L_{S,E}$ $[dB\ re\ 1\ \mu Pa^2m^2s]$ 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.

At time t_i after piling onset, the receptor animal is at range $r_i = r_0 + v_f \cdot t_i$ $[m]$, based on fleeing behaviour defined in section 2.1. 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:

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

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 SEL_{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 SEL_{cum}.

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

After calculating the unweighted SEL_{cum} as described above for each 1/3-octave band, the relevant auditory frequency weightings of Section 1.16 are applied and a weighted broadband value $SEL_{cum,xx}$ is calculated.

4.7.2. SEL_{cum} approach based on fine-resolution sound field

If the sound field of SEL_{ss} is provided in a vertical plane 2D grid along a transect, SEL_{cum} may be calculated directly from this without use of curve fitting. It is assumed that SEL_{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 decimetres. 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), or a suitable exceedance level over depth (see section 1.10). The applied method for evaluation over depth must be justified.

Preferably, all available grid-points may be used for SEL_{cum}. Alternatively, a reduced set of evaluation points using this approach is allowed, provided the method is described and justified.

- 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 1.16. For each point, the broadband frequency weighted $SEL_{ss,xx}$ is calculated.
- Next, the depth dependence is removed by evaluating MOD, or a suitable exceedance level over depth, for each range step throughout the length of the transect.

At time t_i after piling onset, the receptor animal is at range $r_i = r_0 + v_f \cdot t_i \; [m]$, based on fleeing behaviour defined in section 2.1. After these preceding steps, $SEL_{cum,xx}$ is evaluated over the entire piling sequence as:

$$L_{E,cum,xx} = 10 \cdot \log_{10} \sum_{i=1}^{N} \frac{S_i}{100\%} 10^{\frac{L_{E,p,xx}(r_i)}{10}} \; dB$$

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

All hammer strikes of the hammer energy profile 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. For a fleeing receptor animal at constant speed $v_f[\frac{m}{s}]$, this leads to a transition time $\Delta t_s = \frac{s}{v_f}\ [s]$ between two points along the transect.

Let $L_s\ [dB\ re\ 1\ \mu Pa^2m^2]$ be the sound pressure source level of the vibrator.

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

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

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 animal 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 animal at time t_x. Fleeing behaviour is defined in section 2.1.

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 SEL_{cum} as described above for each 1/3-octave band, the relevant auditory frequency weightings of Section 1.16 are applied and a weighted broadband value $SEL_{cum,xx}$ is calculated for each auditory group.

4.8.2. Vibratory driving: SEL_{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, SEL_{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 decimetres. 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), or a suitable exceedance level over depth (see section 1.10). The choice of evaluation over depth must be justified.

Preferably, all available grid-points may be used for SEL_{cum}. Alternatively, a reduced set of evaluation points using this approach is allowed, provided it is described and justified.

Let step-size s [m] be the horizontal spacing between selected evaluation points. For a receptor animal fleeing at constant speed v_f $[\frac{m}{s}]$, 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 1.16. For each point, the broadband frequency weighted $L_{p,rms,xx}$ is calculated.
- Next, the depth dependence is removed by evaluating MOD, or a suitable exceedance level over depth for each range step throughout the length of the transect.

At time t_x after piling onset, the receptor animal is at range $r_x = r_0 + v_f \cdot t_x$ $[m]$, based on fleeing behaviour defined in section 2.1.

After these preceding steps, $SEL_{cum,xx}$ 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 SEL_{cum}.

4.9. 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.

4.10. Numerical example

Disclaimer: The example is based on NMFS (2018) *frequency weightings and metrics (PTS instead of AUD INJ) and is only included as an example of the prognosis procedure.*

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

- Source Level $L_{S,E}$ 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 $N_{PL,E}(r) = X \cdot log_{10}(r) + A \cdot r$ 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

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.

Caution: 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 µPa²s. This is contrasted by the LF animal, which is seen to exceed its PTS threshold for any initial distance within the Distance-To-Threshold $r_{PTS,LF}$ of 27,422 m.

Inspecting the scenario at maximum permitted initial distance $r_0 = 200\ m$, the SEL_{cum} with LF weighting is 198.8 dB re1 µPa²s. This is an excess of 15.8 dB compared to the PTS threshold. With PCW weighting, the SEL_{cum} at the same distance is 177.8 dB, representing a margin of 7.2 dB compared to the threshold value of 185 dB.

1/3-octave band frequency [Hz]	Source Level	Propagation Loss coefficients	
	SL_E [dB re $1\mu Pa^2m^2s$]	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.

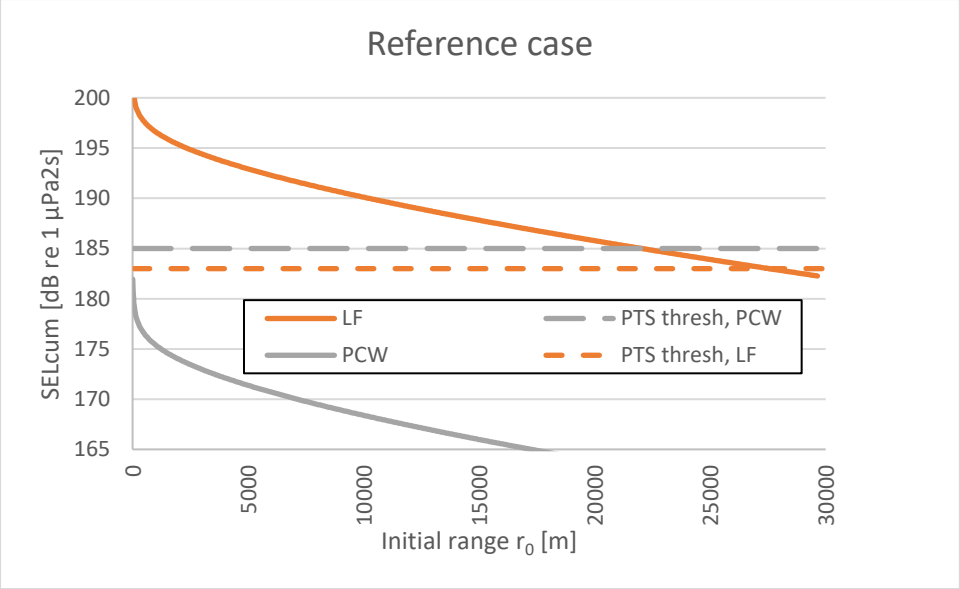


Figure 4: Reference case: Calculated SEL_{cum} as a function of initial distance r_0 for LF and PCW auditory groups. Corresponding PTS thresholds are indicated by dashed lines.

Mitigated 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 16 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 $r_{PTS,LF} = 180\ m$, which fulfils the requirement of a maximum permitted r_{PTS} being less than $r_0 = 200\ m$.

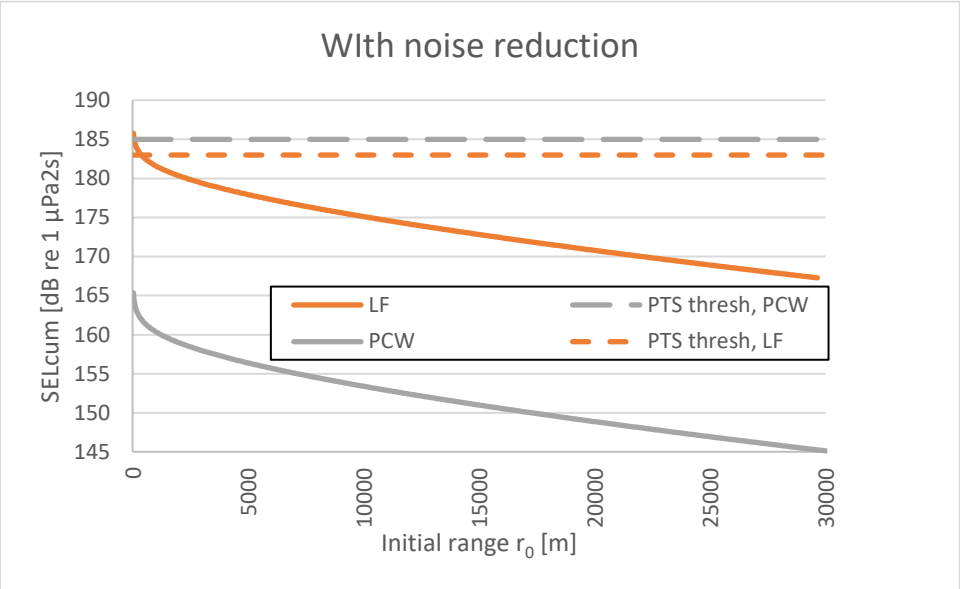


Figure 5: Planned construction scenario: Calculated SEL_{cum} as a function of initial distance r_0 for LF and PCW auditory groups. Corresponding PTS thresholds are indicated by dashed lines.

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

Measurement equipment requirements are given in Appendix A.

5.1. Verification of propagation model

To demonstrate the validity of the Prognosis the Concessionaire is required to perform propagation verification measurements as required in the Conditions. Propagation verification measurements shall be carried out during the installation of the first pile in order to verify the sound propagation model applied in the prognosis.

The Concessionaire may, at an earlier stage, undertake supplementary investigations of sound propagation using an artificial underwater sound source. Any such supplementary investigations shall be technically justified and submitted to the Danish Energy Agency (DEA) for approval prior to execution. These investigations may be used to inform project planning and modelling; however, they shall not replace nor be regarded as equivalent to propagation verification measurements performed during actual pile installation.

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, it must be anticipated that this method will often not provide meaningful results for the lowest 1/3-octave bands. Situations where this is a particular concern include very shallow water and stratified sound speed profiles. On that background, care must be taken to ensure that only frequency bands with physically meaningful results are included.

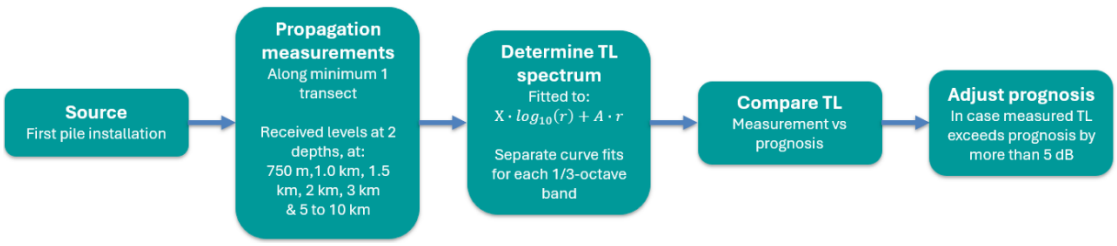


Figure 6: Overview flow diagram for propagation model verification.

For impact piling the measurement metric is SEL_{ss}. For 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 project relevant hearing 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.
- A minimum set of receiver ranges are: 750 m, 1,000 m, 1,500 m, 2,000 m, and 3,000 m. It is also required to include a receiver between 5 to 10 km, ideally chosen as the harbour porpoise behaviour DTT predicted by the prognosis.
- 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 1.12.

The measurements shall be used to determine a transmission loss, based on curve fit to the expression $DL_{TL} = X_{TL} \cdot log_{10}(r) + A_{TL} \cdot r$. Here, X_{TL} and A_{TL} are positive constants. 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 these two versions of transmission loss are compared for all range steps out to 3 km. Here, the Prognosis-based transmission loss shall not at any point exceed the measurement-based transmission loss by more than 5 dB. Hence, a certain conservatism is permitted in the Prognosis model.

For larger deviations, the verification will be considered to have failed. In that case the Concessionaire will have to revise the model to fit the verification measurements.

The Concessionaire shall report the verification to the Danish Energy Agency including a discussion of the agreement between prognosticated and measured data based on the above criteria. 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 1.16 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 Concessionaire is required to perform compliance verification measurements as required in the Project Conditions with the actual piling activity, and as outlined in Figure 7. Verification measurements shall be performed as required in the Conditions, until the installation methods and noise mitigation measures have been adjusted such that requirements are fulfilled for three consecutive pile installations, and this can be demonstrated by the verification measurements. Any correcting actions to comply with the thresholds shall be approved by the Danish Energy Agency.

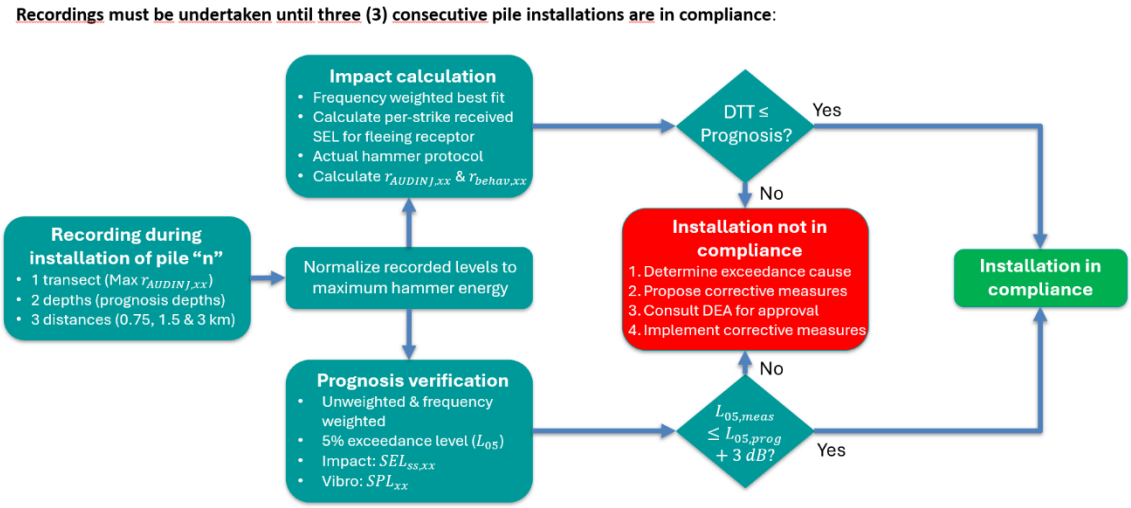


Figure 7: Overview flow diagram for compliance verification.

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 1.12.

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 $DL_{TL} = X_{TL} \cdot log_{10}(r) + A_{TL} \cdot r\ dB$. 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 Concessionaire not to be dependent on a measurement that is less representative for the 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 L_{05}, 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 1.16 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 [20]:

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

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 (see e.g. discussion in [20]) are applied, these must be described.

The measured broadband 5% exceedance levels $L_{05,meas}$ shall be compared to those of the Prognosis ($L_{05,prog}$). If these broadband levels do not exceed those of the Prognosis by more than 3 dB, the Prognosis and verification measurements can be regarded as verified. 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 as described above, it must furthermore be demonstrated that the measurements comply with the acoustic criteria of Section 2, as relates to AUD INJ, and behaviour disturbance DTT for all project relevant hearing groups. This can be demonstrated using the following approach:

One (distance, depth) time-resolved measurement dataset shall be selected as the basis for the SEL_{cum} calculation, without statistical aggregation across strikes or time intervals.

The selected (reference) dataset shall consist of:

- Individual SEL_{ss} values per pile strike (impact piling), or
- Received SPL values in fixed time intervals (e.g. 1 s) for vibratory piling.

Either the Prognosis (see section 4.6) or propagation measurement (see section 5) derived transmission loss, $DL_{TL} = X_{TL} \cdot log_{10}(r) + A_{TL} \cdot r\ dB$, shall be used to interpolate or extrapolate received levels at range $r\ [m]$ based on the reference dataset using the range-dependent received-level function:

$$SEL_R(r) = SEL_{ref} - \left(DL_{TL}(r) - DL_{TL}(r_{ref})\right)\ dB$$

Here, SEL_R is the received level at distance r, based on the measured level SEL_{ref} at distance r_{ref}. The behaviour disturbance DTT for project-relevant hearing groups is calculated iteratively over r using the relationship between SEL and SPL_{125ms} (section 1.2), where DTT is defined as the value of r where SELR is equal to the appropriate behaviour threshold criteria (Table 3, Table 4).

For the calculation of AUD INJ DTT, the animal fleeing behaviour is defined in section 2.1. In the event of pile driving interruptions, the fleeing behaviour is inverted for the duration of the

interruption, meaning the distance to source decreases over time by v_f (see Table 5). For interruptions where an ADD soft start is employed (see section 6), the animal distance at resumption of pile driving is fixed at $r_{ADD,behav,xx}$ as predicted by the Interruption prognosis.For each pile strike (impact piling) or time interval (vibratory piling), the received SEL contribution is determined at the instantaneous receptor animal distance using the range-dependent received-level function throughout the total foundation installation duration. SEL_{cum} is calculated by energetic summation of all received SEL contributions along the receptor animal trajectory, and through an iterative procedure over the receptor animal starting distance r_0 $[m]$ outlined in Figure 3, the AUD INJ DTT is calculated.

Impact verification is deemed satisfactory when behaviour disturbance and the AUD INJ DTT are within the limits established by the Prognosis.

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.

6. Interruption handling during pile driving

As pile driving interruptions may occasionally occur, and as the behaviour of marine mammals in the vicinity during such interruptions is uncertain, a precautionary approach is adopted regarding their assumed position and distance from the installation site upon restart of pile driving.

To avoid harmful impacts on marine mammals following a pile driving interruption, the procedure outlined in Figure 8 shall be complied with.

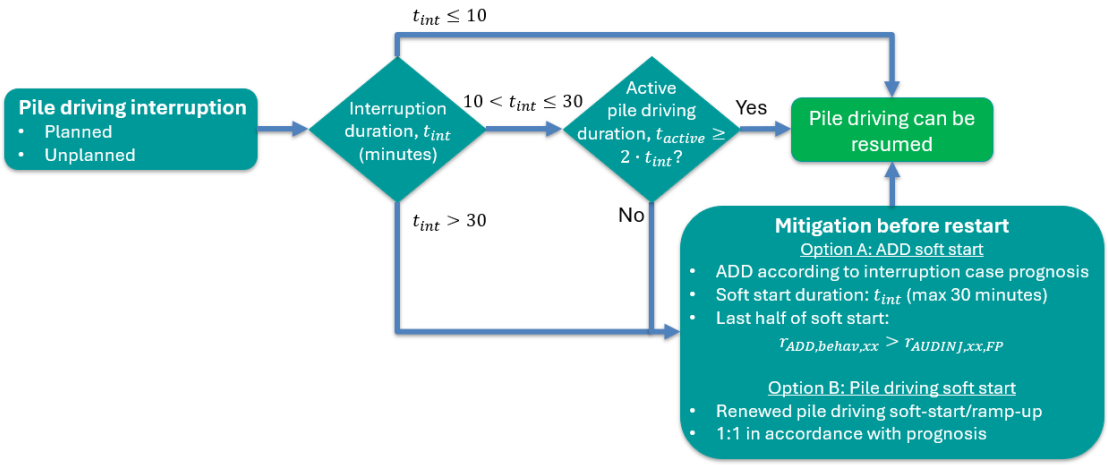


Figure 8: Overview flow diagram for interruption handling and pile driving restart

Where the interruption duration is less than 10 minutes, pile driving may be resumed at the desired hammer energy, irrespective of the stage of the installation process at which the interruption occurred, and without the application of a soft-start procedure.

In cases where the interruption duration is between 10 and 30 minutes, pile driving may be resumed at the intended hammer energy without a soft-start procedure, provided that active pile driving was ongoing for a minimum period corresponding to twice the interruption duration immediately beforehand. This approach is based on a precautionary assessment of marine mammal movement, assuming that previously deterred individuals would not be able to return to proximity associated with potential harm during the interruption.

If active pile driving did not occur for a period corresponding to at least twice the interruption duration prior to the interruption, or if the interruption duration exceeds 30 minutes, deterrence of marine mammals shall be implemented prior to resumption of pile driving at the desired hammer energy. Deterrence may be achieved either through an ADD soft-start procedure, as specified in the Interruption Prognosis, or through a renewed pile-driving soft-start procedure, as assumed in the reference or mitigated Prognosis.

Where an ADD soft start is applied, the distance to injury threshold (AUD INJ DTT) shall not exceed 25 m from any deployed ADD. The ADD soft start duration should correspond to the interruption duration (t_{int}) however limited to a maximum of 30 minutes. The deterrence range, based on species-specific behaviour disturbance criteria (Table 3, Table 4), shall exceed the full-power AUD INJ DTT predicted in the Prognosis, for no less than the last half of the soft start duration before pile driving is resumed.

Note: If bubble curtains or other active noise-mitigation measures are deployed at a distance from the installation site, the ADD setup shall include a sufficient number of active units positioned outside the mitigation perimeter to ensure effective deterrence in all directions from the installation.

A detailed plan for the deployment and use of ADDs during pile-driving interruptions shall be submitted to and approved by the Danish Energy Agency (DEA) prior to construction.

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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.