# Guideline for underwater noise – Installation of impact-driven piles

**Kontor/afdeling**
Center for Energiressourcer

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## Introduction

The concession holder must demonstrate how he intends 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. To do this the concession holder is required to prepare a prognosis for underwater noise and conduct a control measurement programme.

## Requirements for the prognosis

The two main components in the prognosis are the noise source characteristics and the sound propagation characteristics. Further, the expected employed hammer energy and the duration of the piling and number of blows will have bearing on the cumulated noise and shall be described.

The prognosis can be based either on numerical modelling (e.g. Finite Elements modelling) or empirically based estimation.

The prognosis shall be calculated for a specific number of piles as requested in the Conditions.

The purpose of the prognosis is that the concession holder estimates the environmental impact using the given source levels and sound propagation losses and calculate the cumulative SEL experienced by a receptor (marine mammal) while it is fleeing away from the noise source. If necessary, the concession holder shall propose noise mitigation methods, which ensure that the threshold for cumulative SEL is not exceeded at any time during the installation of the wind farm. By noise mitigation methods is understood passive noise mitigation (e.g. damping screens and bubble curtains) as well as active noise mitigation (e.g. reduced source levels and special piling schemes in combination with active monitoring – in case the concession holder should chose to apply such methods).

Noise source characterisation shall comprise:

- Spectrum of the unweighted source piling noise,
- The variation of noise source strength with applied hammer energy (between positions and during installation),
- It is recommended that noise source characterisation also include:
    - The variation of noise source strength with water depth (between positions),

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Amaliegade 44
1256 København K

T: +45 3392 6700
E: ens@ens.dk

www.ens.dk

    - The variation of noise source strength with pile tip depth (during installation).

The sound propagation characterisation shall:

- Include estimation of the spectrum of transmitted noise,
- Take into account the influence of the bathymetry at the site,
- Employ sound velocity profiles covering realistic sound velocity profiles during the expected installation period,
- Take into account the acoustic properties of the topmost sea bed soils.

It is recommended that the transmission characterisation shall:

- Include shear waves in shallow areas,
- Model the boundary conditions at the surface either presuming calm waters or including a surface roughness,
- Include volume attenuation (sea water attenuation) for modelling of frequencies higher than 2 kHz,
- Include in-situ measurements of sound propagation loss for the calibration of the model.

The installation characterisation shall include:

- Expected variation of hammer energy, including variation with pile tip penetration and with location,
- Expected no. of blows at each hammer energy level ('hammer energy curve').

## Requirements for the documentation of the prognosis

The documentation shall provide a detailed description of how the concession holder has prepared the prognosis. As a minimum, the description shall comprise:

- Description of which method had been used for estimating noise source strength,
- Description of which method has been used for estimation of sound propagation loss,
- Discussion of assumptions and simplifications inherent to the chosen model/method,
- Noise source strength as single strike 'broad-band' (at least 12.5 Hz to 2 kHz) SEL and as single strike SEL spectrum in 1/3 octave bands at 100% hammer energy and full pile tip penetration at 750 m distance as well as back-propagated to 1 m distance,
- Depth chart of the bathymetry used for modelling,
- Tables of acoustic properties used for sea bed soils,
- Sound speed profiles used,
- 'Noise maps' showing spatial variation of single strike SEL. It is recommended that at least 18 radials are calculated. The spatial extent of noise maps shall be at least as large as the maximum fleeing distance of harbour porpoise given the expected duration of piling. If the concession holder includes the variation of noise source strength then noise maps shall be provided for each relevant noise source strength level, e.g. beginning of piling, end of piling, 'best location', 'worst location' etc. ,
- Tables with best fit $X \cdot \log_{10}(r) + A \cdot r$ curves approximating the propagation loss in the direction where it is smallest,
- Proposed driving 'history', i.e. no. of blows, starting hammer energy level, end hammer energy level and incremental curve. To be provided as curves and as tables
- Estimated 'efficiency spectrum' of proposed noise mitigation method (third-octave spectrum of insertion loss in dB SEL),
- Cumulative SEL for the driving of the pile(s), calculated with a fleeing animal as described later in this document,
- In the case noise mitigation has to be employed:
    - Single strike broadband SEL, and SEL spectrum in 1/3 octave band in 750 m distance with the noise mitigation fully employed,

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    - Description of how the calculation has been performed.
- Mitigated single strike SEL at 750 m distance has to be calculated at the same hammer energy and at the same depth(s) as the unmitigated SEL.

The best-fit curves shall be used for approximation of the propagation loss and shall be of the type X·$\log_{10}$(r) +A·r, where X and A are positive constants, and r is the distance. They are introduced to allow a simple and transparent calculation of cumulated SEL.

Regardless how the concession holder develops his own model and derives the approximation for the sound propagation it is a requirement that an in-situ validation shall be conducted.

By 'SEL' is understood a scalar metric (in dB re 1 μ$Pa^2$s) proportional to the amount of energy which is encompassed in the strike duration T. It is defined as:

$$SEL = 10 * \log_{10} \frac{E}{E_0}$$

Where $E = \int_0^T p^2(t)dt$ is the value of the energy curve during the strike duration and $E_0 = p_0^2 * T_0$, where $p_0$ = 1 μPa is the reference sound pressure and $T_0$ = 1 s is the reference time. *T* is the integration time in s corresponding to the duration of the sound event. It is recommended that T is determined by $t_{95} – t_5$, where $t_{95}$ and $t_5$ are the instances on the energy curve where 95% and 5 % of the signal energy are reached.

If a pile driving technique is employed where the hammer strikes at a higher frequency than one blow per second it may not be possible to identify the single events as required by the above definition. In that case the following approximate estimate may be used:

$$SEL \approx L_{eqT} + 10 * \log_{10} \frac{T}{nT_0},$$

where $L_{eqT}$ is the equivalent continuous sound level, *T* is the averaging period during continuous pile driving, *n* is the number of pile strikes during the period (according to the hammer log) and $T_0$ is 1 s. $L_{eqT}$ is given by:

$$L_{eqT} = 10 * \log_{10} \frac{\int_0^T p^2(t)dt}{Tp_0^2},$$

where *p*, $p_0$ and *T* are defined as above.

An averaging period of 30 s is recommended.

By 'SEL spectrum' is understood the energy spectrum in dB re 1 μ$Pa^2$s per 1/3-octave band as obtained by integration of the energy spectrum density (in dB re 1 μ$Pa^2$s/Hz) calculated by the Fourier transform of the recorded signal time series. The overall value of this spectrum is equal to the single value SEL.

## Requirements for control measurements

To demonstrate the validity of the prognosis the bidder is required to perform control measurements as required in the Conditions.

If the threshold on cumulative SEL is not met, control 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 control measurements.

Measurements shall be performed with the purpose of accurately and rapidly determining the cumulated SEL of the pile installation, and shall thus:

- Allow determination of SEL for each hammer strike,
- Employ calibrated omnidirectional hydrophones with a sensitivity deviation of less than ±2 dB up to 40 kHz in the horizontal plane and less than ±3 dB up to 40 kHz in the vertical plane,
- It is recommended that a calibration signal is recorded,
- Be conducted for the entire pile installation duration,
- Be performed in 750 m distance ±5% and shall be distance-corrected to 750 m using the approximated $X \cdot \log_{10}(r) + A \cdot r$ propagation loss function,
- Be performed at two different depths, at 66% and 33% water depth (but in no case less than 2 m below the sea surface),
- Be recorded in a frequency range at least ranging from 12.5 Hz to 20 kHz,
- Be recorded in .wav-format at 44.1 kHz sampling rate and 16 bit resolution or better or in similar lossless format.

As the pressure field is known to oscillate with a wavelength of around 80 m 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.

Subsequent reporting shall:

- Report calculated and measured SEL for each blow in tables and as curves,
- Include used hammer force for each hammer strike in tables and curves,
- Include hydrophone data and calibration,
- Be conducted for the entire pile installation duration,
- Provide position of measurement station, and hydrophone depths,
- Report results from different depths both separately and as the average of the two,
- Report details of calculation of correction,
- Be calculated for the frequency range between 12.5 Hz and 20 kHz,
- Report measurement data in .wav-format at 44.1 kHz sampling rate and 16 bit resolution or better or in similar lossless format.

In order to validate the sound propagation model and the approximated best fit $X \cdot \log_{10}(r) + A \cdot r$ -curves transect measurements shall also be performed as required in the Conditions.

To reduce the risk related to obtaining transect measurement that does not comply with the model, the concession holder may at an earlier time perform transect measurements using e.g. an airgun as source.

The transect measurements shall be performed by short duration hydrophone deployment at a number of different distances. The transect shall be oriented in the direction with the assumed least propagation loss. Reference data shall be recorded at 750 m distance, using this as a reference distance.

The transect measurements shall:

- Report the agreement between the sound propagation model and the transect validation measurements,
- If performed prior to piling: Comprise measurements at the distances 375 m, 500 m, 1000 m, 1500 m and 3000 m besides the reference measurements at 750 m distance from the source point
- If performed during piling: Comprise measurements at the distances 375 m, 500 m, 1000 m, and 1500 m from the pile besides the control/reference measurements at 750 m distance from the pile. It is recommended that measurements are also made at 3000 m distance,
- Be performed at the same depth as the shallowest control measurement i.e. at a depth equal to 33% of the water depth at the location of the control measurement at 750 m distance. Thus, is the control measurements are e.g. made at 5 and 10 m depth then the transect measurements shall be made at 5 m depth,
- Report details of calculation of level correction due to distance,
- Be performed and calculated for the frequency range between 12.5 Hz and 20 kHz,
- Be recorded and reported in .wav-format at 44.1 kHz sampling rate and 16 bit resolution or better or in similar 'lossless' format.

Each point value in the transect measurement may deviate ±3 dB from the approximated best-fit curve. However, the deviations must not be single-sided; if all measurements are either higher or lower than the best-fit curve, the validation will be considered to have turned out negatively. In that case the concession holder will have to revise his model in order to fit the validation measurements or perform a new validation. The concession holder shall report the validation to the Danish Energy Agency including a discussion of the agreement between approximation and measured data. In case of disagreement between approximation and validation measurements it is required that the report can be accepted by the Danish Energy Agency before installation can commence or continue.

## Requirements on the use of seal scrammers

At each pile a seal scrammer shall be operated in order to scare marine mammals and avoid causing trauma. First a pinger shall be used as an initial deterrent because the seal scrammer emits noise at a quite high level. Then the seal scrammer shall be turned on and finally piling can commence.

As many different more or less efficient makes/models of seal scrammers are available on the market, the Danish Energy Agency requires to approve the type of seal scrammer, that the concessionaire plans to use.

The first hammer strikes shall be at the lowest possible energy level to allow marine animals to swim as far away as possible before hammer energy is gradually increased as installation progresses. The timing of events shall be such that animals can flee at least to a distance of c. 2 km before the first hammer strike.

## Method for calculation of cumulative SEL including animal flight

In order to avoid misunderstandings and results which are difficult to compare the bidder shall calculate cumulative SEL including animal flight using the following simplified model.

The calculation of cumulative SEL is performed with a 'virtual animal'-receptor with an initial distance of 1.3 km from the pile at the onset of piling. This distance corresponds to the effective radius of scramming of harbour porpoises using seal scrammers.

Animal fleeing can be assumed to take place radially away from the pile with a constant speed, $v_f$ = 1.5 m/s.

The cumulative SEL is calculated as the summation of the total sound energy to which the receptor is exposed during the duration of the piling.
The SEL corresponding to 100% hammer energy is given by:

$$SEL_{Max} = 10 * \log_{10} \frac{E_{100\%}}{E_0}$$

Where $SEL_{Max}$ is the single strike SEL @ 1 m distance from pile in dB re. 1 µPa$^2$s at 100% hammer energy.
The energy of the i'th strike out of a total of N strikes is related to the maximum energy by: $E_{i\%} = \frac{S_i}{100\%} * E_{100\%}$, where $S_i$ is the percentage of full hammer energy of the i'th strike.

By a receptor in a distance $r_i$ from the source in m, the energy received from the i'th strike will depend of the energy of the i'th strike as well as the propagation loss and thus be:

$$E_i = \frac{S_i}{100\%} * E_0 * 10^{\frac{SEL_{Max} - L_{PL}(r_i)}{10}}$$

Where the sound propagation loss, $L_{PL}$, is approximated by:

$$L_{PL}(r_i) = X * \log_{10} r_i + A * r_i = X * \log_{10}(r_0 + v_f * \Delta t_i) + A * (r_0 + v_f * \Delta t_i)_i$$

Where $X$ and $A$ are the constants of the best fit approximation to the sound propagation loss, $r_0$ is the receptor's distance to the pile in m at the onset of piling, $v_f$ is the fleeing speed in m/s and $\Delta t_i$ is the time from the onset of piling to the onset of the i'th strike in s.

The sound propagation loss shall be approximated as a best fit to the sound propagation maps in the direction with the least sound propagation loss.

The cumulative SEL is given by:

$$SEL_C = \log_{10}\frac{\sum E_i}{E_0} = 10 * \log_{10}\sum_{i=1}^{N}\frac{S_i}{100\%} * 10^{\left(\frac{SEL_{Max} - L_{PL}(r_i)}{10}\right)}$$

Finally, inserting the term for the sound propagation loss the cumulative SEL for the entire pile installation can now be calculated by the following term:

$$SEL_C = 10 * \log_{10}\sum_{i=1}^{N}\frac{S_i}{100\%} * 10^{\left(\frac{SEL_{Max} - X * \log_{10}(r_0 + v_f * \Delta t_i) - A * (r_0 + v_f * \Delta t_i)}{10}\right)}$$

If $SEL_{Max}$ is prognosticated at several depths then the largest value must be used for the calculation of $SEL_C$.

## Calculation example

Using the following input parameters for an example calculation:

- $SEL_{Max}$ is 219.1 dB ,
- 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 average transmission loss is estimated by 14.72 $\cdot \log_{10}(r)$ + 0.00027$\cdot$r,
- Fleeing speed is 1.5 m/s and animals are initially scrammed out to a distance of 1.3 km before onset of pile driving.

Then, the cumulative SEL experienced by a fleeing animal can be calculated as 194.0 dB given the guidelines above. As the threshold is 190 dB then the cumulative SEL will have to be reduced by 4.0 dB to fulfil requirements.