Emne:	Marine mammals and underwater noise in relation to pile driving – Working Group 2014
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Indledning

Anlæg af havmølleparker medfører udvikling og brug af stadigt større vindmøller og dermed tilsvarende større fundamenter. I forbindelse med Horns Rev 3 havmøllepark blev der i VVM-undersøgelsen beregnet støjudbredelse for monopæl-fundamenter med en diameter op til 10 m. I takt med stigningen af fundamentstørrelser, vil støjniveauet ligeledes stige. Dette medfører en øget risiko for at påvirke det marine dyreliv negativt.

I kraft af stigende støjniveauer ønsker Naturstyrelsen og Energistyrelsen at der etableres et grundlag for hvorledes Danmark skal regulere anlægsstøjen fra installation af rammede fundamenter i forbindelse med havmølleparker i danske farvande.

I forbindelse med udbud af Horns Rev 3 havmølleparken i den danske del af Nordsøen, har Energinet.dk derfor udarbejdet anbefalinger for regulering samt forberedt retningslinjer for, hvorledes koncessionshaver kan lave prognoser for undervandsstøj fra rammede fundamenter og dokumentere at reguleringens krav overholdes.

Dette notat har til formål at give et overblik over den bio-akustiske argumentation der er til grund for den anbefalede regulering. Endvidere indeholder notatet detaljerede akustiske retningslinjer for beregning, måling og dokumentation af undervandsstøj fra installation af rammede fundamenter.

Arbejdet er udført med udgangspunkt i Horns Rev 3, men hensigten er, at konklusionerne, med mindre justeringer, også kan benyttes i forbindelse med andre, fremtidige vindmølleprojekter i danske farvande.

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1. Introduction

In June 2014 Energinet.dk formed a working group with the task of investigating how underwater noise from the installation of impact driven foundations at the planned offshore wind farms could be regulated in order to take due consideration of protected marine species. It was the wish that the work of the group could be used as basis for setting forth the regulation for Horns Rev 3 as well as being generalised to serve as basis for future regulation of underwater noise.

The group conducted a sequence of seminars and presented the preliminary results to the Danish Nature Agency and the Danish Energy Agency on September 1st 2014. Based on this presentation the agencies prepared and agreed the regulation for Horns Rev 3.

This present memorandum contains a written description of the findings and recommendations of the working group, which include recommendations on future regulation on underwater noise from pile driving.

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2. Objectives for regulation of noise

Loud underwater noise can have a range of detrimental effects on marine mammals. Two types of effects have received most attention: disturbance of behaviour and damage to the auditory system. Other effects, which are not discussed here, include masking of other sounds, including communication sounds; physical damage (blast injury); physiological effects (e.g. increased stress hormone levels) and vestibular effects (noise-induced nausea).

In general, there are two objectives governing the regulation of underwater noise: protection of individuals and management of populations. (1) The need to protect individuals is dictated by common perception of animal welfare, i.e. a general objection to activities which can cause death or harm to animals, in particular large mammals and birds. (2) The need to protect populations from a general wish to maintain good conservation status for ecosystems and individual species. Whether one of the two objectives should be considered more important than the other is a political rather than scientific decision. The relevant point here is that the measures required to fulfil one objective may not be relevant for the other objective. In other words, the two goals may require separate efforts.

2.1 Noise-induced hearing loss

The lowest noise-induced effect on hearing is a so-called temporary hearing loss (TTS, sometimes also called auditory fatigue), which manifests itself as a temporarily elevated threshold of hearing after exposure to loud sounds. In humans, this is the effect commonly experienced after attending a rock concert or after experiencing a loud firecracker or explosion.

TTS is in general localised to frequencies around and immediately above the frequency range of the noise which caused the TTS. This means that TTS induced by pile driving noise typically only affects the hearing at low frequencies (Kastelein et al., 2013b). TTS, being temporary by definition, will disappear within minutes for minimum exposures to hours and even days following severe exposures.
At even higher levels of noise exposure the hearing threshold does not recover fully, but leaves a smaller or larger amount of permanent threshold shift (PTS), see Figure 1. This permanent threshold shift is a result of damage to the sensory cells in the inner ear and is thus different from and should be kept apart from the general age-related hearing loss (presbyacusis) known from humans and also some marine mammals. An initial TTS of 50 dB or higher is generally considered to carry a significantly increased risk of generating a PTS (Ketten 2012). Lower levels of TTS can, if repeatedly induced, also lead to PTS.

As PTS thresholds for ethical reasons cannot be measured directly in experiments, the agreed approach to estimate thresholds for PTS is by extrapolation from TTS thresholds to the noise exposure predicted to induce 50 dB of TTS and thus a significant risk of PTS. This extrapolation is not trivial, however, as it is complicated by the fact that the relationship between exposure and amount of initial TTS is not proportional. Thus, one dB of added noise above the threshold can induce more than one dB of additional TTS, see Figure 1. The slope of the TTS growth-curve differs from experiment to experiment and slopes as high as 4 dB of TTS per dB of additional noise has been observed in a harbour porpoise (Lucke et al., 2009).

2.2 Criteria for hearing damage from pile driving noise

Pile driving noise is sufficiently loud to be capable of inducing TTS and PTS in marine mammals present around the pile driving site. As most of the energy in pile driving noise is at low frequencies it is expected that TTS and PTS will also manifest itself at low frequencies. Very little is known about the importance of low frequency hearing in seals and porpoises. Harbour seals rely on low frequency sounds for communication during mating (e.g. Bjørgesæter et al., 2004). Harbour porpoises do not vocalise at low frequencies, but use low frequency hearing passively as part of their auditory scene analysis. Therefore, it is not possible to conclude what the long term consequences for survival and reproduction a hearing loss at low frequencies could have for seals and porpoises.

However, referring to the animal welfare objective mentioned above, the group concluded that deliberately inflicting PTS in marine mammals is not acceptable and thus appropriate measures should be taken during pile driving to avoid exposures above the threshold for PTS.

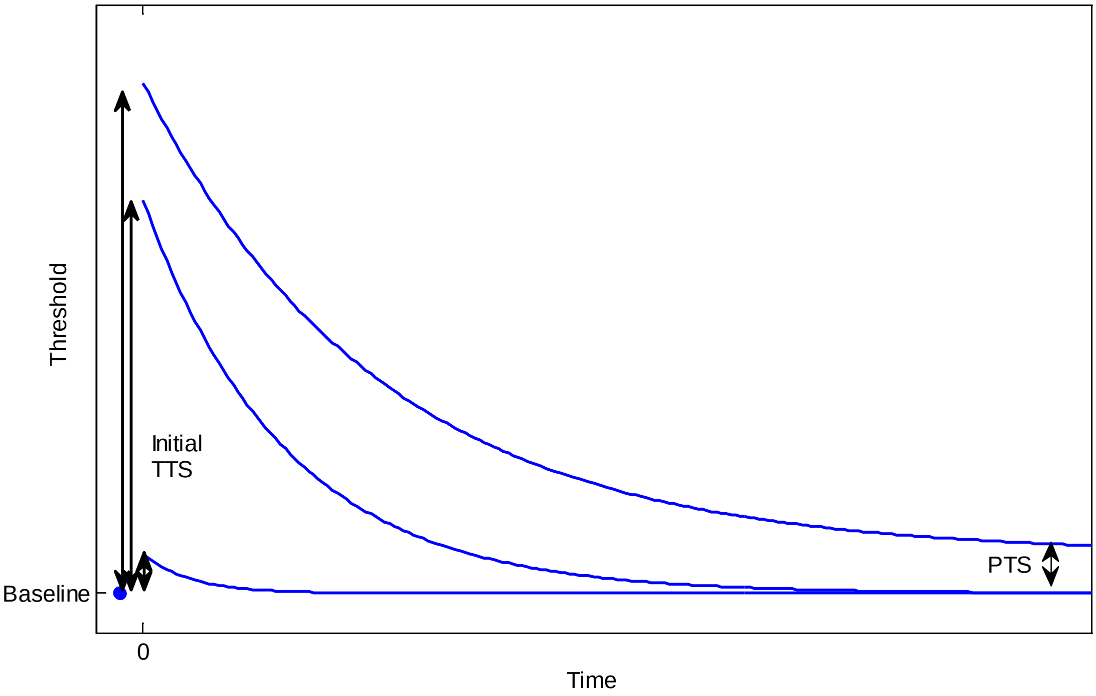

Figure 1 Illustration of development of and recovery from TTS. TTS is induced at time 0 where a smaller or larger increase in the threshold occurs. The threshold drops back towards baseline with time. For low and intermediate levels of noise exposure the threshold is completely restored, for the highest level of exposure a smaller PTS remains.

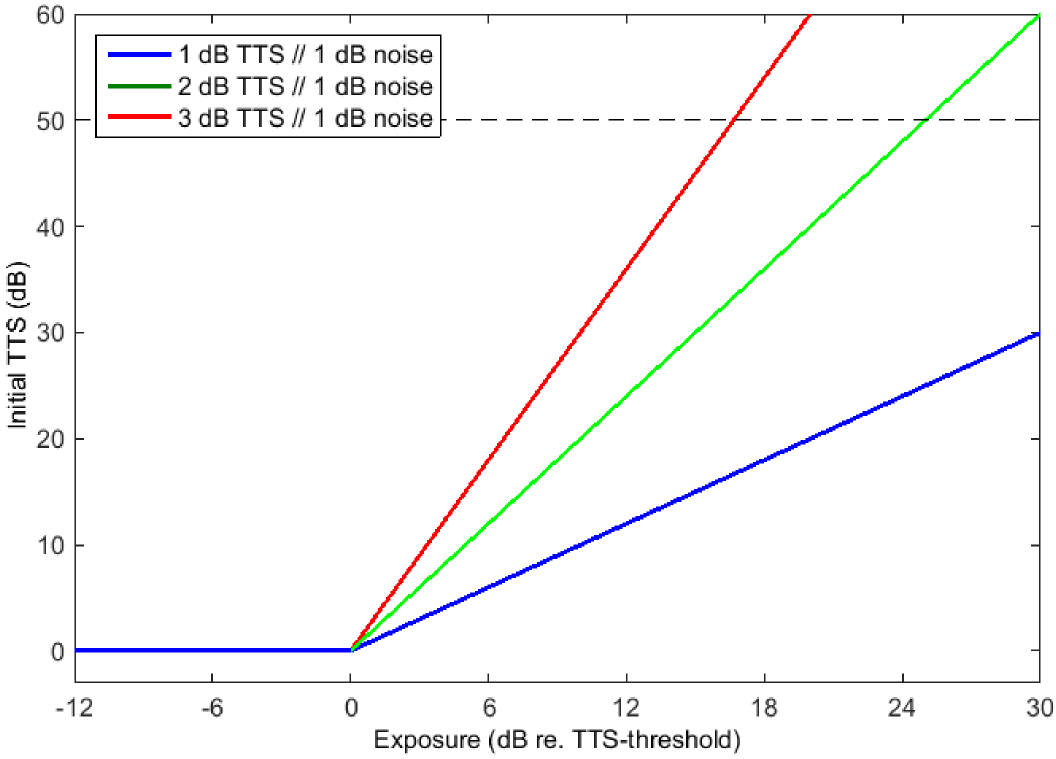

Figure 2 Schematic illustration of the growth of initial TTS with increasing noise exposure. Three different slopes are indicated. Note that the real curves are not necessarily linear. Broken line indicate threshold for inducing PTS, assumed to be at 50 dB initial TTS.

2.3 Thresholds for inducing TTS and PTS

Substantial uncertainty is connected to the question of how the fact that animals do not hear equaly well at all frequencies should be handled when assessing risk for inflicting TTS and PTS. Southall et al. (2007) proposed that frequencies should be weighted with a fairly broad weighting function (M-weighting) which only removes very low and very high frequencies, well outside the range of best hearing for the animals. Separate weighting functions were developed for different groups of marine mammals. Others have proposed a more restrictive weighting with a weighting filter function resembling the inversed audiogram (e.g. Terhune, 2013). In the light of this uncertainty and given that TTS thresholds from experiments are given in unweighted levels the working group decided to proceed with unweighted levels, further supported by this approach being highly precautionary (Southall et al., 2007).

A number of experiments have been conducted on TTS in seals and porpoises. The immediately relevant results are summarized in Table 1 and Table 2. The relevant unit for expressing thresholds has been debated intensively and this debate resulted in double criteria presented by Southall et al., 2007. Thresholds were expressed both as maximum instantaneous pressure (peak pressure) and cumulated acoustic energy (sound exposure level, SEL). The difference between the two thresholds is pronounced, as the SEL takes into account the duration of the noise exposure whereas peak pressure ignores duration. It now seems that there is general consensus on SEL as a better predictor of TTS than peak pressure (Tougaard et al. 2015) and only SEL is considered in the following.

SEL is defined by Southall et al. (2007) as the decibel level of the cumulative sum-of-square pressures over the duration of a sound for sustained non-pulse sounds where the exposure is of a constant nature. Southall et al. (2007) also remarks that this measure is extremely useful for pulses and transient non-pulse sounds because it allows sounds of differing duration to be characterised in terms of total energy for assessing exposure risk. Finally, Southall et al. (2007) stress that the SEL metric enables integration of sound energy across multiple exposures from sources such as seismic airguns, pile driving and sonar signals and put forward the following expression:

$$SEL = 10 * \log_{10} \frac{\sum_{n=1}^{N} \int_0^T p_n^2(t)dt}{p_{ref}^2}$$

With this expression SEL has the unit dB re. 1 μPa^{2}s.

Table 1 Experiments where TTS and PTS thresholds for harbour seals were measured or could be inferred.

Harbour seals	**Reference**	**Level**	**Stimulus**	**Comments**
PTS	Southall et al., 2007	186 dB SEL M-weighted	General	Extrapolated PTS-threshold based on TTS-measurements from California sea lion, bottlenose dolphin and beluga
	Kastak et al., 2008	202 dB SEL unweighted	4.1 kHz pure tone	Level that induced small PTS in a harbour seal by an experimental error
	Kastelein et al., 2013a	199 dB SEL unweighted	4 kHz octave band noise	Level that induced severe TTS (44 dB) in a harbour seal, at the brink of PTS

TTS	Southall et al., 2007	171 dB SEL M-weighted	General	Extrapolated from TTS-thresholds on bottlenose dolphin and beluga
	Kastelein et al., 2012a	169-176 dB SEL unweighted	4 kHz octave band noise	TTS-thresholds measured on a harbour seal
	Kastak et al., 2005	182 dB SEL unweighted	2.5 kHz octave band noise	TTS-threshold measured on a harbour seal

2.4 TTS and PTS in seals

Southall et al. (2007) estimated TTS and PTS thresholds for seals in general, but these estimates were based on data from bottlenose dolphins, beluga and a single California sea lion. However, since 2007 actual measurements from harbour seals have become available and are used here instead to estimate thresholds.

PTS was induced in a harbour seal due to an experimental error by Kastak et al. (2008). This means that an actual measurement is available. In fact, a second experiment (in a different facility and on a different animal) produced a very strong TTS (44 dB) by accident, which is considered to have been very close to inducing PTS. By combining the two experiments a threshold for PTS in harbour seals is tentatively set to 200 dB re. 1 $\mu Pa^2 s$.
TTS was induced in two harbour seals with octave band noise centred on 2.5 kHz and 4 kHz, respectively. Simply taking the mean of the thresholds produces an estimated threshold for TTS of 176 dB re. 1 $\mu Pa^2 s$.

Table 2 Experiments where TTS and PTS thresholds for harbour porpoises were measured or could be inferred.

Harbour porpoise	**Reference**	**Level**	**Stimulus**	**Comments**
PTS	*Southall et al., 2007*	198 dB SEL M-weighted	General	Extrapolated from TTS-thresholds on bottlenose dolphin and beluga
	Popov et al., 2011	183 dB SEL unweighted	45 kHz octaveband noise	Level that induced severe TTS (45 dB) in a finless porpoise, at the brink of PTS
TTS	*Lucke et al., 2009*	164 dB SEL unweighted	Single airgun pulse	TTS-threshold measured on a harbour porpoise
	Kastelein et al., 2012b	163-172 dB SEL unweighted	Continuous octave-band noise 4 kHz	TTS-thresholds measured on a harbour porpoise
	Kastelein et al., 2014	189-197 dB SEL unweighted	Continuous pure tone 1.5 kHz	TTS-thresholds measured on a harbour porpoise
	Popov et al., 2011	<163 dB SEL unweighted	45 kHz octaveband noise	Extrapolated threshold for TTS in a finless porpoise

2.5 PTS and TTS in harbour porpoises

A threshold for inducing PTS in high-frequency cetaceans, including harbour porpoises, was proposed by Southall et al. (2007). However, this threshold is based solely on experimental data from mid-frequency cetaceans (bottlenose dolphins and beluga) and is no longer considered representative. Only one study is directly relevant to PTS and this was performed on a sister species to the harbour porpoise, the finless porpoise. Popov et al. (2011) were able to induce very high levels of

TTS (45 dB) by presenting octaveband noise centred on 45 kHz. The energy in this noise was at considerably higher frequency than the main energy of pile driving noise. As the hearing of porpoises at 45 kHz is much better than at frequencies below a few kHz where the pile driving noise energy is present, it is likely that this proposed threshold underestimates the threshold for inducing PTS by pile driving noise, i.e. the threshold for PTS for pile driving noise is likely to be higher than 183 dB re. 1 μPa^{2}s. How much higher is not possible to say at present, so the 183 dB re. 1 μPa^{2}s is retained as the threshold as a precautionary measure.

Several studies on TTS in harbour porpoises are available. However, only Lucke et al. (2009) is directly relevant to pile driving. Lucke et al. (2009) measured TTS induced by exposure to single air gun pulses. The three other studies used other stimuli of longer duration and thus considered less representative for pile driving noise. As the threshold of Lucke et al. (2009) furthermore is the lowest of all the thresholds measured this threshold is retained for precautionary reasons.

Table 3. Proposed thresholds for inducing TTS and PTS in harbour seals and harbour porpoises by pile driving noise. See text for justification of values. Unit are defined as culmulative sound exposure (SEL) unweighted

	Harbour seal	**Harbour porpoise**
TTS	176 dB re. 1 μPa^{2}s	164 dB re. 1 μPa^{2}s
PTS	200 dB re. 1 μPa^{2}s	183 dB re. 1 μPa^{2}s

The grey seal is also widely distributed in the Danish waters, but no information on the TTS and PTS level for this species is available. Until experiments are made on grey seals we suggest using the thresholds for harbour seals. Also, white beaked dolphins and minke whales live in the Danish North Sea. However, hardly any information is available on hearing and sensitivity to noise in these species, and the group was not able to provide advice on TTS and PTS thresholds.

3. Disturbance of behaviour

Noise which is not loud enough to induce TTS or PTS can still have an impact on marine mammals, as it may affect and alter the behaviour of the animals, which again can carry implications for the long-term survival, and reproductive success of individual animals. Thereby, if a sufficiently large number of individuals are affected, also the status of the population can be affected, see Figure 3. Effects come as two different types. The most direct effect is through outright panic reactions to the noise in which case direct mortalities could be the result, as a fleeing animal might be caught in a gill net (Wright et al. 2013) or a small and not yet independent calf may become separated from its mother. More common, however, is probably the less severe effects where displacement of animals to less favourable areas or disturbance to feeding or mating behaviour will lead to a reduced energy intake and reduced mating success, which in turn again affects the population. The sequence of events is also illustrated in Figure 4 where it is also suggested how regulation of impact through behavioural effects of noise could be approached. It seems desirable to seek a population-based criterion for noise exposure such that:

- If the conservation status is favourable the population size must not be negatively affected
- If the conservation status is not favourable the growth of the population must not be affected, i.e. the ability to achieve good conservation status must not be compromised
- The long term survival of local populations must not be compromised

Based on some independent information about the conservation status of the population an acceptable limit of disturbance may be determined as some small, additional mortality permitted by the activity under evaluation (pile driving or other). Given a firm understanding of how immediate behavioural changes (displacement and changes to foraging and mating behaviour) can translate into population level effects, it becomes possible to go back up through the model, see Figure 3, combine this with information about sound levels, sound transmission and animal densities and then derive a maximum tolerated sound exposure for the given activity. However, the knowledge about how immediate, short-term changes to behaviour are translated into population level effects is so incomplete for seals and harbour porpoises that such a method of regulation is completely unrealistic within the near future. The group thus agreed that it is at present not possible to derive exposure limits based on management objectives for the conservation status of the population. Furthermore, as the uncertainty of current monitoring methods is considerable and the natural variation very large, it is unlikely that it will be possible to detect changes in population size or growth rates directly and unequivocally relate these to pile driving operations.

In the absence of a population-based criterion, it is only possible to make a criteria relating to how many animals are affected by the noise, without knowledge of the consequences. Everything else being equal, the more animals which are affected and the longer the impact lasts, the larger the impact on the population must be.

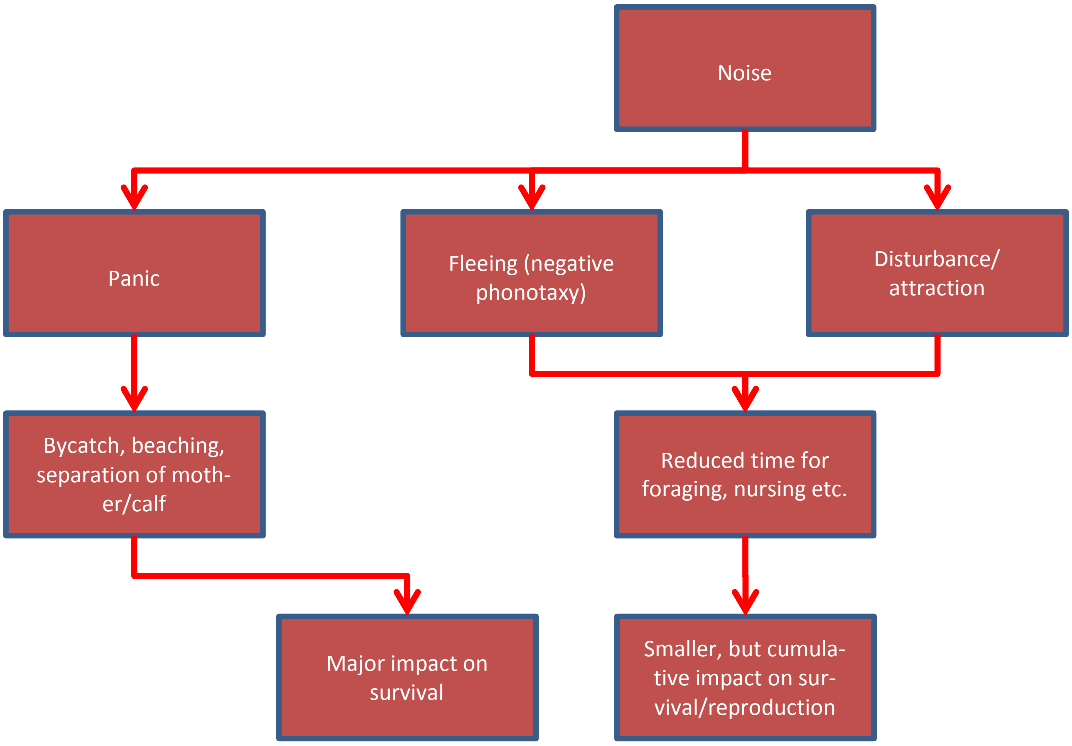

Figure 3. Schematic illustration of mechanisms by which noise-induced changes to behaviour can lead to effects on short-term and long-term survival and reproduction (fitness) in marine mammals.

3.1 Criteria for behavioural effects

When it comes to determining thresholds for behavioural reactions to noise there is first of all considerable disagreement among authors on the best noise measure to use. There is, however, general support to the suggestion that sound pressure is a better overall predictor for reactions than for example sound energy cumulated over long periods (such as across all pile driving pulses within a complete piling operation). As was the case for TTS and PTS thresholds, there is also not agreement on how to perform frequency weighting when computing sound levels. However, as long as we are only concerned with pile driving noise this disagreement is not critical, as the individual pile driving pulses are very similar to each other and the different parameters such as peak level, rms-average and single stroke SEL are highly correlated.

3.2 Reaction thresholds for seals and porpoises

Several studies have studied behavioural reactions of porpoises to pile driving noise. These are summarised in Table 4. Of these, Dähne et al. (2013) is considered the most reliable, as it is based on a large and well-balanced dataset and a threshold for reactions could be established. This leads to a tentative threshold for pile driving noise causing negative phonotaxis (fleeing) in porpoises of 140 dB re. 1 µPa^{2}s single pulse SEL, unweighted.

Table 4. Field studies where porpoise reactions to pile driving has been investigated. Unit in three first studies is rms-average sound pressure level (unweighted) whereas it is single pulse SEL, unweighted in the last. Values are thus not directly comparable.

Reference	**Level**	**Stimulus**	**Comments**
Tougaard et al., 2009	130 dB re. 1 µPa rms	Pile driving Horns Reef I	A threshold was not established
Brandt et al., 2011	149 dB re. 1 µPa rms	Pile driving Horns Reef II	Likely overestimated, as excess attenuation of reef was not included
Tougaard et al., 2012	130 dB re. 1 µPa rms	Play back	Not a real pile driving
Dähne et al., 2013	140 dB re. 1 µPa^{2}s SEL	Pile driving at Alpha Ventus	Supported by aerial surveys

Very limited information is available on the reactions of seals to pile driving. A single study on ringed seals in the Arctic (Blackwell et al., 2004) studied reactions (or rather the absence of reactions) of ringed seals to conductor tube piling on an artificial island, but as these settings are very different from offshore wind turbine installation in the North Sea this study has not been considered. It is thus at present not possible to provide a reaction threshold for seals.

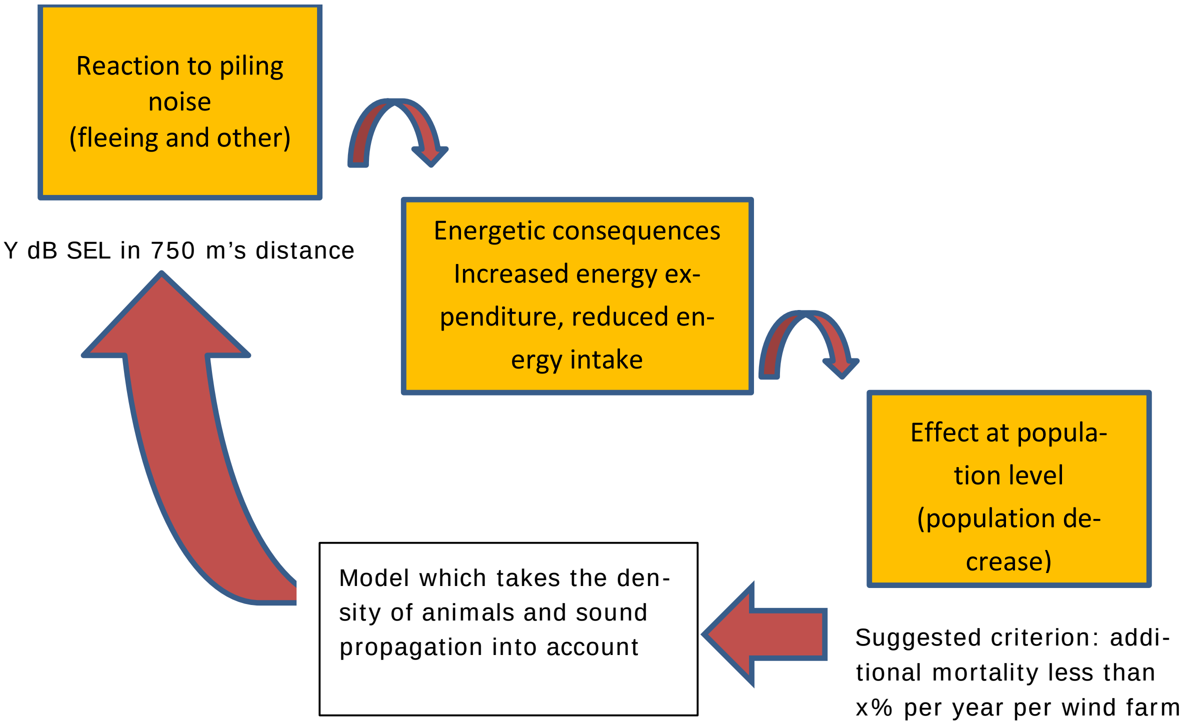

Figure 4. Sequence of events leading from noise exposure to population level effects and suggestion as to how a population-based exposure criterion could be fed backwards up the chain and lead to an exposure limit. Model modified from the PCAD model of National Research Council, 2005.

3.3 Mitigation

A reduction of the impact of noise on marine mammals can be achieved by three different methods:

1. Reduction of the generated noise
   - Reduces the source of the impact
   - Achieved by modification of installation methods
   - Reduces impact distances for TTS/PTS and behaviour

2. Reduction of the radiated noise
   - Reduces the impacted area
   - Achieved by bubble curtains or other acoustic screens

3. Reduces impact distances for TTS/PTS and behaviourReduction of the received noise
   - Reduces the exposure to animals by deterrence prior to construction or by restrictions on time of year where piling can occur
   - Deterrence (pingers and seal scarers) reduces impact from TTS/PTS but does not mitigate impact on behaviour
   - Restrictions in periods with high occurrence of animals reduces impact on behaviour

3.4 Requirements for mitigation

Mitigating the effects of pile driving noise on marine mammals can be done through several measures. Using alternative methods for driving the pile into the substrate can reduce the intensity of the generated sound pressures as well as the frequency content (Betke and Matuchek, 2010). The noise transmission can also be reduced secondarily through the use of bubble curtains, cofferdams etc. (CALTRANS, 2009, Lucke et al., 2011). Finally, mitigation can be done by removing animals from the affected area. Scientific evidence show that seal scarers cause aversive behaviour in harbour porpoises out to several kilometres distance (Brandt et al., 2013, Dähne et al., 2013). The deterrence effect of the seal scarers on porpoises is not 100%, and the better the habitat is for the animals, the less effective the seal scarer is likely to be. Therefore a smaller number of individuals will likely be present in the area even after the use of seal scarers. Data of seal scarers deterring effect on seals is still inconclusive as seals are extremely difficult to observe at the surface and they do not vocalize regularly like porpoises, therefore proper experiments have not been conducted (Fjälling et al., 2006, Götz and Janik, 2013).

Seal scarers emit loud sounds pressures intense enough to induce changes in hearing thresholds (PTS/TTS) in both harbour porpoises and seals at close range. They should therefore be used with caution to reduce this risk. Pingers were developed to alert harbour porpoises to the presence of fishing gear to avoid by-catch (Lien et al. 1992). They emit a lower intensity sound to cause less abrupt aversive behaviour than seal scarers. Pingers are, however, not able to keep the majority of animals at a safe distance from the pile, but can be employed to initially divert animals out to a “TTS/PTS safe” area before switching the seal scarer on. If sound mitigation devices are used, this procedure is therefore recommended as best practice.

4. Recommendations

It is recommended that the emissions of underwater noise from installation of driven foundations is regulated in the following way:

- A threshold is set of 183 dB cumulated SEL (unweighted) for harbour porpoise and 200 dB cumulated SEL (unweighted) for seals,
- Initial use of pinger and subsequent seal scarer should be considered as a requirement,
- The calculation of cumulated SEL shall include the effect with and without initial scaring and include the effect of animal fleeing behaviour,
- The construction contractor is required to prepare a prognosis to demonstrate how they plan to adhere to regulations,
- The construction contractor is required to perform actual measurements to document that they adhere to regulations and conditions given in the permission,
- All above general requirements are laid out in the Conditions,
- Technical details and specific requirements for calculations, measurement, and documentation are laid out in a separate document: ‘Guideline’.

Particularly in relation to the use of pingers and seal scarers, it must be noted that special care must be taken when considering the introduction of strong artificial noise sources as a mitigation measure. It is central to make sure that the mitigating measure (the pinger and seal scarer) does not by itself create an impact comparable to or even larger than the impact one is trying to mitigate (the pile driving). It is therefore required to model cumulated effects for both unmitigated and mitigated scenarios.

4.1 Input to Guideline document

The sections following describe the model and the required input in more technical detail.

4.2 Technical requirements - Guideline

The construction contractor must demonstrate how they intend to fulfil the requirements on limitation of environmental impact caused by emitted underwater noise as set forth by The Danish Energy Agency. To do this, the construction contractor is required to prepare a prognosis for underwater noise and conduct a control measurement programme.

4.2.1 *Requirements for the prognosis*

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

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

The prognosis shall be prepared for a specific number of piles as requested separately (in the Conditions).

The purpose of the prognosis is that the construction contractor estimates the environmental impact using the given source levels and sound propagation losses and calculates the cumulative SEL experienced by a receptor (marine mammal) while it is fleeing away from the noise source. If necessary, the construction contractor shall propose noise mitigation methods that ensure the threshold for cumulative SEL is not exceeded. Here, noise mitigation methods are understood as 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 of:

- Underwater sound 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 include:
    - The variation of noise source strength with water depth (between positions),
    - The variation of noise source strength with pile tip depth (during installation).

The sound propagation characterisation shall:

- Include estimation of the frequency spectrum of transmitted noise with distance,
- 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,
- Include volume attenuation for modelling of frequencies higher than 2 kHz,
- 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 an appropriate surface roughness
- Include in-situ measurements of underwater 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 number of strikes for each hammer energy level (‘hammer energy curve’).

4.2.2 *Requirements for the documentation of the prognosis*

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

- 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’ (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 pene-

tration at 750 m distance and at a depth of 1/3 and 2/3 of the water depth 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 $X \cdot \log 10(r) + \alpha \cdot r$ 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 in the form of damping 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,
    - 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.
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The best-fit curves shall be used for approximation of the propagation loss and shall be of the type $X \cdot \log_{10}(r) + \alpha \cdot r$, where X and α 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 μPa²s) numerically equivalent to the amount of energy which is encompassed in the strike duration T. It is defined by:

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

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 for single strike SEL. *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 (Madsen, 2005).

In signal analysis it is customary to use the term ‘energy’ in the sense of the integral of the square of a signal, without regard to its units. This should not be confused with the potential energy density of the sound field.

Cumulative SEL is defined by :

$$SEL_C = \log_{10} \frac{\sum E_i}{E_0}$$

Where E_i is the energy of the i’th sound event.

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 due to overlap between successive pulses. 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 numerical equivalent to the sound energy spectrum in dB re 1 μPa^2s per 1/3-octave band. The SEL spectrum is obtained by integration of the energy spectrum density (in dB re 1 μPa^2s/Hz) which can be calculated by the Fourier transform of the recorded signal time series. The overall value (sum of all bands) of this spectrum is equal to the single value SEL.

4.2.3 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 for 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 $X \cdot \log_{10}(r) + \alpha \cdot r$ 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.

Subsequent reporting shall:

- Report calculated and measured SEL for each blow in tables and as curves as well as the cumulative SEL for the whole driving period,
- 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 dB-level of the two,
- Report details of calculation of distance 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. Corrections shall be made for changes to temperature and salinity between time of validation and time of installation.

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 shallow 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.

4.2.4 Requirements on the use of seal scarers

If the use of seal scarers has been prescribed then they shall be operated in the following way.
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 at quite high level. Then the seal scrammer shall be turned on and finally piling can commence. 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.

4.2.5 Method for calculation of cumulative SEL including animal flight

In order to avoid misunderstanding 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 from the pile at the onset of piling.

For the preparation of EIA’s the following is required: 1) A reference calculation shall be performed without the use of initial scramming. In this case the initial distance shall be defined in the EIA. For numerical reasons it can be considered not to use values close to zero for starting distance but instead include a specific distance of the animals to the pile. This is based on the assumption that an applied “soft start” procedure with very few blows and extremely soft blows gives the animals time to flee out to a certain distance before the onset on regular piling (still starting as softly as possible). The exact starting distance will be determined by the features of the soft-start procedure employed in the project 2) A similar calculation shall be performed which include the effect of scramming. The distance effect shall be discussed based on recent results.

Animal fleeing is 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 equivalent 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 equivalent 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. The received energy will be reduced proportionally with the percentage of full hammer energy and the sound propagation loss encountered during transmission to the distance r_i and thus be:

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

The sound propagation loss shall be approximated by:

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

where X and α are the constants of the best curve 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 Δt_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:

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

4.2.6 Example calculation of cumulated SEL

Using the following input parameters for an example calculation:

- SEL_{Max} is 219.1 dB (single strike for a 6000 mm pile installed with a blow energy of 1800 kJ as estimated by Subacoustech for the EIA),
- 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 3 s,
- The average transmission loss is estimated by $14.2 \cdot \log_{10}(r) + 0.00043 \cdot r$,
- Fleeing speed is 1.5 m/s and animals are initially scrammed out to a distance of 2 km before onset of pile driving.

Then, the cumulative SEL experienced by a fleeing animal can be calculated as 191.1 dB given the guidelines above. If the threshold is 183 dB then the source level, SEL_{Max} will have to be reduced by 8.1 dB to fulfil requirements.

5. Outlook and discussion

A number of important questions remain unanswered after the working group completed the recommendations. Part of this is due to the limited time available to the group, but the main reason is the presence of major gaps in our current understanding of the effects of pile driving noise on marine mammals. The most pressing issues are briefly discussed below in order to provide an outlook in the direction where future effort should be directed.

5.1 New results on TTS in porpoises

After the working group finished its work new results on TTS induced in a harbour porpoise by exposure to pile driving noise became available (Kastelein et al., submitted). As the results are still unpublished and only available as a draft manuscript (courtesy of Ron Kastelein) it was decided that the group's recommendations should remain unchanged at present, awaiting peer review and proper publication of the results. However, for completeness, the preliminary conclusions from the manuscript are included here. A harbour porpoise in captivity was subjected to long exposures (1 hour) of pile driving noise played back at reduced levels. Cumulated sound exposure levels of 180 dB re. 1 μPa^2s (unweighted) and above resulted in TTS at 4 and 8 kHz but not at 2 kHz or higher than 8 kHz. This threshold level is 16 dB higher than the threshold reported by Lucke et al. (2009) and only 3 dB lower than the tentative PTS threshold provided by the working group. It is too early to conclude on the reason(s) for the 16 dB discrepancy between the two studies – whether it is due to differences in the stimulus paradigm (one very powerful airgun pulse vs. 1 hour of repeated weak pile driving pulses), reflects differences in sensitivity between the two animals tested, or whether there may be experimental errors in one or the other study. One important caveat in the new study, is that the hearing was only measured after 1 hour, therefore, it is unknown whether TTS occurred before this hour had past, if this is the case the onset of TTS did occur at lower sound levels than presented above. Nevertheless, the new result does not affect the working group's conclusion that PTS is likely to be inflicted by pile driving noise at cumulated sound exposure levels above 183 dB re. 1 μPa^2s (unweighted), and that the true threshold for PTS is likely to be somewhat higher than this.

5.2 Frequency weighting

The issue of frequency weighting was touched upon above but has not been dealt with in detail. Although the group acknowledged the need for frequency weighting in general assessments of noise impact, the proposed exposure limits were given as unweighted levels. This is justified by the relatively stereotypic nature of pile driving noise, which means that actual measurements, experimental results and criteria all are likely to be affected to the approximately same degree by frequency weighting, no matter whether one selects loudness-based weighting (M-Weighting, Southall et al. 2007) or weighting with basis in the audiogram (Tougaard et al., 2014). It is expected that discussions and studies over the coming years will lead to consensus and common recommendations regarding frequency weighting.

5.3 Temporal weighting of noise in TTS experiments

A central open question when comparing results from different TTS studies is the importance of the temporal structure of the fatiguing noise. There are experiments on harbour porpoises which indicates that recovery from TTS can occur in breaks between repeatedly presented sound pulses, which means that the overall cumulated energy may not be sufficient to predict TTS, also the duty cycle is important (Kastelein et al., 2014). This has important implications for the regulation of pile driving noise, as the pulse interval may be a significant parameter when it comes to inducing TTS.

5.4 Efficiency of deterrence

As mentioned above (3.4 Requirements for mitigation) there is good evidence that seal scarers are effective in deterring harbour porpoises. Very limited evidence is available, however, on their effect on seals (despite the name). It seems prudent to conduct dedicated field studies on seals to verify that seal scarers are in fact working as intended and to estimate deterrence distances, which can be used in regulation to minimise PTS in seals.

5.5 Population effects of behavioural disturbance and deterrence

The by far largest knowledge gap is the connection between immediate behavioural effects (deterrence, change in behaviour, etc.) and long term effects on vital parameters (adult and calf survival, fecundity etc.). It is unlikely that this connection can be established through experimental studies and field observations on harbour porpoises. This is primarily because such studies requires that one can observe the same individuals over extended periods (years) and track their reproductive success. This may be possible under certain circumstances for harbour seals, as they rest and give birth on land and can be individually identified. Harbour porpoises on the other hand roam large areas and have so far been impossible to identify individually in the field and apparently have no concentrated areas where they give birth to their calves. At present, the only option appears to be individual based modelling, where the movement, foraging and reproduction of a large number of individual porpoises are modelled in a computer model. A central feature of such models is that the vital population parameters are not coded into the model but appears as output (so-called “emergent properties”). Relevant disturbances, such as pile driving activity can be introduced in the model and the resulting effects on the emergent vital statistics can be studied by means of the model. Such models are under development (Nabe-Nielsen et al., 2013; Thomsen et al 2013), most notably through the DEPONS and DRAMAD projects (http://depons.au.dk/currently/, Thomsen et al., 2013) and are expected to deliver the first preliminary results in the coming years.

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