EFFECTS OF LARGER TURBINES FOR THE OFFSHORE WIND FARM AT KRIEGER'S FLAK SWEDEN

Addendum with revised and extended assessment of impact on marine mammals

Scientific Report from DCE – Danish Centre for Environment and Energy No. 366 2020

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Abstract: The prior assessment of consequences for marine mammals of construction of an offshore wind farm on Krieger's Flak, Sweden, has been updated. This update was prompted by changes in the specifications of the wind farm, new information on noise abatement systems and improved methods for quantitative assessment of acoustic disturbance to harbour porpoises. Results show that pile driving of monopile foundations at Krieger's Flak is likely to present a significant impact on harbour porpoises, harbour seals and grey seals in the area, if performed without measures to reduce the radiated noise from the piling. If, however, an adequate noise abatement system, such as an air bubble curtain, is used, the predicted impact is reduced to a level, where it is assessed to constitute only minor impact on the marine mammal populations in the area and the nearby NATURA2000 sites.

Keywords: Offshore wind energy, harbour porpoises, underwater noise, impact assessment

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Contents

Preface

This report has been commissioned by Vattenfall A/S and constitutes an addendum to the previous assessment report (Tougaard & Mikaelsen 2018). The present addendum contains revised modelling of impact ranges prompted by changes in the project as specified by Vattenfall, recently updated information about efficacy of mitigation measures (air bubble curtains) and a request from Swedish authorities for a more thorough assessment of impact on harbour porpoise behaviour. The assessment of impact on harbour porpoises and evaluation of mitigation measures described in this report thus replaces the assessment in the previous report, but otherwise the two reports should be read as a whole.

Modelling of the sound propagation from pile driving was performed by Mark Mikaelsen; modelling of cumulative sound exposure was done by Mark Mikaelsen and Jakob Tougaard in cooperation; assessments and writing of the report was done by Jakob Tougaard. The report was scoped in discussions with Vattenfall A/S, who also commented a draft version of the report. These comments asked for clarifications and extensions to the text, but did not question the methods used or the assessments performed.

Summary

Construction and operation of an offshore wind farm on the Swedish part of Krieger's Flak has previously been assessed with respect to impacts on marine mammals (Tougaard & Mikaelsen 2018). This report presents an updated and extended assessment of the previous report, based on a revision of the specification of the pile driving operations, improved information on noise abatement systems and improved methods for assessment of behavioural disturbance.

Impact was modelled and assessed for pile driving of steel monopiles, either 11 m or 12 m diameter, at a worst-case location within the wind farm area, bordering the nearby Natura2000 site Sydvästskånes Udstövatten. Impact was assessed for piling with and without use of a noise abatement system, exemplified by the double Big Bubble Curtain. The modelling without noise abatement system was included for reference only.

Results of the modelling and conclusions of the assessments were:

- Pile driving without use of an adequate noise abatement system is likely to present a significant impact to marine mammals, both in the form of risk of inflicting permanent damage to their hearing system and disturbance to animals over a wide area, including the nearby Natura2000 area.

- Use of a noise abatement system with sound attenuation properties comparable to, or better than the double Big Bubble Curtain, will reduce the radiated noise and hence also the impact considerably:

    - There is no risk of inflicting permanent damage to the hearing of seals or porpoises, provided an efficient deterrence of the animals is conducted prior to start of the pile driving.

    - A low number of seals and porpoises are at risk of experiencing low levels of temporary hearing loss (TTS). The affected frequency range means that the TTS does not interfere with porpoise echolocation or communication and full recovery will be within hours after the pile driving. The impact on seals and porpoises is therefore considered minor.

    - Noise from the pile driving is predicted to be capable of affecting the behaviour of porpoises out to a distance of 5-10 km. By combining with modelled data for porpoise abundance, the number of affected porpoises were estimated to be 12 and 4 per foundation for summer and winter, respectively. As the duration of the disturbance is likely to be low, about 6 hours, the impact on porpoises by disturbance is assessed to be minor.

    - Although a quantitative assessment could not be made for seals, it was assessed that the impact on seals is likely to be comparable or smaller than the impact on porpoises. The impact of pile driving on harbour seals and grey seals is thus assessed to be minor.

- A large part of the impacted area, both with respect to effects on hearing and behaviour, is likely to be within the nearby Natura2000 area. However, the number of animals affected is low, in particular during winter months, and the duration of the impact short-lived. The impact on the Natura2000 area Sydvästskånes Udstjövatten is assessed to be minor. The Natura2000 site Falsterbo-Foteviken is too far away from the construction site to be affected by the pile driving.

- The impact from underwater noise from the turbines during operation of the wind farm is assessed to be low and constitute a minor impact on seals and porpoises.

Finally, it is noted that the currently available noise abatement systems are so efficient that there is reason to caution against the common practice of employing acoustic deterrence devices in the form of seal scarers prior to onset of pile driving, as the seal scarer may constitute a source of disturbance equal to or even exceeding the pile driving itself. Effective mitigation of injury to the hearing of marine mammals rely on such deterrence, but the type and intensity of deterrence devices should be adapted to the conditions.

1. Background

Vattenfall AB, Sweden has previously obtained a permission from the Swedish authorities to build and operate an offshore wind farm on Kriegers Flak in the Western Baltic. Details about the project itself can be found in the Environmental Impact Assessment and background documents. Most importantly, with respect to underwater noise and marine mammals, is the updated assessment of effects of pile driving on marine mammals (Tougaard & Mikaelsen 2018), where general background about marine mammals in the area and the wind farm can be found.

In September 2019 comments ("Yttrande") were received from Naturhistoriska Riksmuseet (via Länsstyrelsen Skåne), addressing effects of underwater noise on the Natura 2000 area Sydvästskånes utsjövatten. A number of specific points were raised, summarised in the following, and addressed through the revised and expanded assessment in the following chapters. Focus in the following is on the critically endangered population of harbour porpoises (*Phocoena phocoena*) of the Baltic Proper (Carlén *et al.* 2018), with additional comments on other marine mammal populations.

1.1 Yttrande from Naturhistoriska Riksmuseet

The comments from Naturhistoriska Riksmuseet (2019) are listed in **Table 1.1**, together with the action taken to address the issues.

Table 1.1. Summary of the points raised by Naturhistoriska Riksmuseet (2019) in response to the previous assessment (Tougaard & Mikaelsen 2018) and the actions taken in the present assessment.

Issue raised	Response
a) Focus should be critically endangered Baltic porpoises.	Agreed and incorporated throughout
b) Seal populations are not in favourable conservation status	Seals incorporated in the discussion part. Porpoises are generally considered more vulnerable than seals. Thus, the general assumption is that adequate precautionary measures against impact on harbour porpoises will also provide protection of seals.
c) Behavioural reaction distances are adapted from studies made in the North Sea, where sound propagation conditions are different form the Baltic and from piling of smaller monopiles than in the current proposed project.	New approach to predicting and quantifying the impact on porpoises, based on realistic sound propagation modelling and empirical reaction thresholds, rather than simple reaction distances.
d) Unclear whether maximum distance for behavioural effects refers to the distance where the density decreases (due to animals being deterred) or where the density increases (due to influx of deterred animals)	Clarified to be the maximum distance where the behaviour is affected by the noise, i.e. where animals are swimming away from the sound and the density thus decreased.
e) Concern for increased underwater noise from larger turbines, compared to available measurements from older, smaller turbines.	The limited information available on this issue is discussed.
f) Concern for negative impact from deterrence sounds used prior to piling as a mitigation measure against injury.	Genuine concern, which is addressed in the discussion.

Most important in the revision has been the development of a quantitative assessment of behavioural impact, based on empirical response thresholds (Tougaard *et al.* 2015), appropriate sound propagation modelling (Tougaard & Mikaelsen 2018) and spatial modelling of porpoise abundance (Carlén et al. 2018). Secondly, the assessment of injury (hearing loss) has been updated to reflect changes in monopile diameter and specifications for efficacy of the noise abatement system.

2. Harbour porpoises and noise

A general introduction to underwater noise and effects on marine mammals was provided in Tougaard and Mikaelsen (2018). The relevant sections are updated below and these include justification of the criteria and thresholds used in the assessments.

2.1 Instantaneous intensity vs. accumulated dose

When discussing effects of noise it is important to make a distinction between the acute sound pressure level and the accumulated acoustic energy. A useful analogy comes from toxicology, where some substances are acutely toxic, in which case one is concerned only with the concentration of the toxin in the air breathed or food ingested. Other substances accumulate in the body, in which case the total dose accumulated over time becomes important. In acoustics, there are impacts, such as behavioural reactions, where the best predictor of a response is the instantaneous[1] sound pressure level, adequately frequency weighted (Tougaard et al. 2015); whereas other impacts, most notably hearing threshold shifts (TTS and PTS), are better predicted by the accumulated (time-integrated) acoustic energy (Tougaard et al. 2015, Southall *et al.* 2019).

This difference in how effects are best predicted, either based on the acute exposure (sound pressure level) or by cumulated dose (sound exposure level), means that it is not possible to define a single threshold, which can cover all effects. It is possible to have long-term sound exposure at low levels, which creates little behavioural effects, but which induce hearing threshold shifts (Kastelein *et al.* 2016) and equally possible to have short sounds, which induce behavioural reactions, but without any effects on hearing thresholds. The impact of pile driving on both behaviour and the risk of injury (hearing loss) must thus be treated separately.

2.2 Hearing loss

The mammalian inner ear is adapted to be extremely sensitive to sound, and it is therefore a well-established assumption that injury from exposure to sound will manifest itself in the inner ear before any other tissue (Southall *et al.* 2007). A precursor for actual injury to the auditory system is the so-called temporary threshold shift (TTS), which is the well-known temporary reduced hearing following exposure to loud sound (such as for example a rock concert or an explosion). TTS is also referred to as "auditory fatigue" and is believed to be related to metabolic changes in the hair cells of the inner ear and / or higher neural pathways (Ryan *et al.* 2016). Recovery from small amounts of TTS is fast (minutes to hours) and complete, whereas large threshold shifts (40-50 dB) increases the risk that recovery is incomplete and therefore leaves the animal with a smaller, but permanent hearing loss (Permanent Threshold Shift, PTS).

Criteria for auditory injury for marine mammals are based on TTS because the required sound levels to induce TTS can be measured reliably in captive animals. From these measurements, it is customary to extrapolate to levels

[1] With instantaneous should be understood the sound pressure level averaged over a very short time, less than one second and equal to the temporal integration time of the mammalian ear.

required to induce PTS. For porpoises and impulsive sound this is done by adding 15 dB to the level required to induce TTS, which is considered highly conservative and thus precautionary for the animals. See Tougaard and Mikaelsen (2018) for further details and Southall et al. (2007) for in-depth justification of this approach.

Bottom line in this is that the appropriate acoustic measure when assessing PTS (and hence acoustic injury) is cumulated acoustic energy (sound exposure level, SEL), frequency weighted with an appropriate weighting curve to adjust for the fact that animals are not equally sensitive to sound at different frequencies. See Tougaard and Mikaelsen (2018) for further details and elsewhere for in-depth treatment (Tougaard et al. 2015, National Marine Fisheries Service 2016, Southall et al. 2019).

Experimental evidence indicates a difference between so-called impulsive sounds and non-impulsive sounds in their capability to induce TTS (and hence likely also PTS), where impulsive sounds have the largest impact. Impulsive sounds are poorly defined (see for example Southall et al. 2007), but share some common features which include a sharp onset and short duration (small time-bandwidth product). Good examples of impulsive sounds are shock waves from explosions and pile driving at close range. In contrast, some intense and short sounds, which are not considered impulses, are sonar pings and seal scarer sounds. A complicating factor is the effect of sound propagation on impulsiveness. As an acoustic impulse propagates through the water, it gradually loses the defining features of an impulse, as any sound has a tendency to expand in time with distance from the source (due to differences in sound speed with frequency and multipath propagation). This means that at some distance from an impulsive sound source, the sound can no longer be considered impulsive. However, the conservative (precautionary) approach to this phenomenon is to ignore it and use the lower (and hence precautionary) impulsive threshold throughout the assessment. The consequence is that maximum impact ranges will be overestimated. The lowest sound exposure levels capable of inducing TTS in marine mammals, including harbour porpoises and seals have been assessed by National Marine Fisheries Service (2016), and Southall et al. (2019), and extrapolated to thresholds for PTS. These thresholds are given in **Table 2.1** and are expressed as the sound exposure level, weighted by the appropriate auditory frequency weighting curve and cumulated over the duration of exposure (up to a maximum of 24 hours).

Table 2.1. Thresholds for inducing temporary and permanent thresholds shifts (TTS and PTS, respectively) in seals and porpoises, for impulsive and non-impulsive sounds. The two relevant thresholds for the assessment are indicated in **bold**. From Southall et al. (2019).

Noise type	Species group	TTS [dB re. 1 µPa2s weighted[2]]	PTS [dB re. 1 µPa2s weighted[2]]
Impulsive	Seals	170	185
	Porpoises	140	155
Non-impulsive	Seals	181	201
	Porpoises	153	173

[2] Frequency weighted depending on species, sensu Southall et al. (2019): porpoises VHF-weighting; harbour and grey seals: PCW-weighting.

For assessment of pile driving noise effects on porpoises, this means that the relevant measure is an estimate of the sum of the acoustic energy of all pile driving pulses that a porpoise may be exposed to during installation of a single foundation. This is done below with the method devised by Skjellerup *et al.* (2015). Details can be found in Tougaard and Mikaelsen (2018), but in brief consists of the following steps:

1. The source level and frequency spectrum of the pile driving noise for the relevant monopile diameter is estimated from available data.

2. A transmission loss function is estimated from modelling sound propagation from one or more locations at Krieger's Flak, using bathymetry data and realistic assumptions about hydrography, sediment structure etc.

3. By combining a piling scenario, where a generic sequence of pile driving strokes are delivered to the monopile with gradually increasing hammer energy and a simple model for escape behaviour of porpoises, the VHF-weighted sound exposure level of each individual pulse can be estimated at the position of the porpoise.

4. The total exposure is found as the sum of all pulses received at the porpoise.

5. This cumulated sound exposure level (SELcum) can be compared to the lowest level capable of inducing PTS (155 dB re. 1 μPa^2s, VHF-weighted) to determine whether porpoises are likely to experience PTS or not.

The entire set of calculations can be repeated for different scenarios, such as with and without the use of sound dampening measures.

2.2.1 Biological significance of TTS

Almost nothing is known about the short-term and long-term consequences of a hearing loss in wild marine mammals. Nevertheless, the onset of permanent hearing loss (PTS) serves as a well-defined and precautionary criterion for injury in porpoises and seals. It is less evident with temporary threshold shifts (TTS). Some consider also TTS an unwanted impact on the animals (see for example German Federal Ministry for the Environment and Nuclear Safety 2013). However, the consequences for a porpoise of suffering a small elevation in hearing threshold at low frequencies, which recovers completely within a few hours at most (Popov *et al.* 2011), are likely to be very low. TTS induced by pile driving noise occurs at very low frequencies, well outside the frequencies used for echolocation and communication (Kastelein *et al.* 2015). Neither echolocation, nor communication between mother and calf will thus be affected by TTS induced by pile driving noise. The overall effect of inducing small amounts of TTS in porpoises as a consequence of pile driving is thus assessed to be insignificant for the long-term survival and reproduction of the animal, and thus in turn also without any effects at the level of the population.

2.3 Disturbance of behaviour

Harbour porpoises are known to react behaviourally to pile driving noise at distances of tens of km for pile driving without sound dampening measures installed (Tougaard *et al.* 2009, Brandt *et al.* 2011, Dähne *et al.* 2013) and it is also known that reaction distances can be reduced considerably by application of sound dampening measures, such as air bubble curtains (Dähne *et al.* 2017). Based on the maximum reaction distances, a lowest sound level capable of disturbing porpoises was estimated to be about 140 dB re. 1 µPa^{2}s, expressed as single pulse, unweighted sound exposure level by Dähne et al. (2013). While this threshold is likely to be applicable to pile driving noise in general, for piling without sound dampening measures, the fact that it is not appropriately frequency weighted means that it cannot be used to predict reactions when sound dampening measures are used. This is because the efficacy of sound dampening measures generally increases with frequency, which means that the beneficial effect of the dampening is likely to be underestimated unless an appropriate frequency weighting is included (Tougaard & Dähne 2017). Also the fact that the threshold is expressed as acoustic energy rather than a sound pressure level may be inappropriate, cf. section 2.1 above.

A review of results from behavioural reactions to noise in wild porpoises was performed by Tougaard et al. (2015). This review proposes a generic response threshold of a sound pressure level 40-50 dB above the hearing threshold (audiogram) of the porpoise[3], which corresponds to about 100 dB re. 1 µPa VHF-weighted. This generalized and frequency-weighted threshold is found as the sum of the threshold of hearing across frequencies of best hearing (about 45 dB re. 1 µPa, Kastelein *et al.* 2010) and a sensation level of 45 dB.

In addition to frequency weighting, the sounds must also be averaged over an appropriate time window, approximating the auditory integration time of porpoises (Tougaard et al. 2015, Tougaard & Beedholm 2019), which is on the order of 0.1 s. This is coincidentally very close to the duration of pile driving pulses, which means that any adjustment for sound duration is of little importance for this type of sounds.

Assessment of behavioural disturbance is then performed through a spatially explicit modelling of sound pressure levels around the pile driving site when maximum hammer energy is used. The iso-level contour corresponding to a sound pressure level of 100 dB re. 1 µPa VHF-weighted thus expresses the estimated zone around the pile driving site, where porpoises can be expected to react to the noise. This spatially explicit zone can be used to derive average and maximum disturbance ranges, but can also be combined with similar spatially explicit information about porpoise abundance. If one knows the exposed area and the density of animals per km^2 in the disturbed area, one can estimate the absolute number of animals that will be disturbed by the pile driving noise. This estimate only represents an average of what can be expected and is associated with substantial uncertainty. This uncertainty comes from the natural variation in distribution of porpoises in the area and variation between porpoises in how responsive they are to sound. The estimated numbers should thus not be taken as indications of the actual number of porpoises, which will be affected by the pile driving, as this can never be predicted in advance, but instead as an indication of the scale of the impact on the local population and on the Natura2000 area Sydvästskånes Udsjövatten.

[3] Such a level above the hearing threshold is sometimes referred to as “sensation level”.

2.3.1 Seals

In principle, the same type of analysis could be performed for seals, providing estimates of the number of seals likely to be disturbed by the pile driving noise. This has not been attempted, however, as neither of the two central prerequisites for the analysis is available: a generalized response threshold and a spatial model for seal density.

A few studies have looked at responses of seals to pile driving noise and they indicate that reaction distances are comparable to reaction distances in porpoises, i.e. tens of km for pile driving without noise abatement systems (Russell *et al.* 2016).

3. Mitigation measures

In general, impact from noise can be mitigated through three different (but not mutually exclusive) methods:

- Reduction of the generated noise. This refers to modifications to the source itself, which results in less acoustic energy being generated in the first place. For a noisy machine, this could for example be a change in design from a diesel engine to an electric engine.

- Reduction of the radiated noise. This refers to various dampening and shielding methods, which reduces the acoustical energy propagating away from the sound source. For a noisy machine, this could be fitting it with mufflers or shielding screens.

- Reduction of the received noise. This refers to methods that reduces the noise received by humans and animals around the source. For a noisy machine, this could be moving the machine further away from humans / animals or only using the machine, when no, or only few, animals are around.

All three approaches can be used when reducing the risk of impact of pile driving on marine mammals. The first approach involves changing the design of the hydraulic hammer and / or the way the hammer strikes the pile; the second approach involves attenuating the noise from the pile, by acoustic absorbers or screens; and the third approach involves piling only at times when no animals are within the impact zone. The latter can be achieved by either planning the construction work at a time of the year when few or no animals are in the area (if possible), or actively deterring animals from the impact zone by means of acoustic deterrence devices deployed immediately prior to pile driving. Two methods are considered relevant for the Krieger's Flak Offshore Wind Farm and are discussed below.

3.1 Acoustic dampening

Several systems to dampen the radiated noise from pile driving have been developed in recent years. A good review of shallow-water systems is found in Rodkin and Pommerenck (2014) and recent reviews of large-scale system for deeper waters relevant for offshore piling are found in Nehls and Bellmann (2016) and Koschinski and Lüdemann (2019). One of the commercially available systems, which have proved to be efficient in attenuating pile driving noise in waters 20-30 m deep is the so-called Big-Bubble Curtain from Hydrotechnik Lübeck (see for eample Bellmann *et al.* 2014, Dähne et al. 2017). The system consists of one or two circular air hoses placed on the seabed around the monopile and fed with air from large compressors on the bubble curtain vessel (**Figure 3.1**). The rising air bubbles from the hoses create a bubble curtain of air, which both reflects (and thus retains) the sound within the circle and absorbs and dissipates the acoustic energy as heat.

The different noise dampening systems are capable of attenuating the noise considerably, however, with a strong frequency dependence. Compilation of measurements on several different systems can be found in for example Bellmann *et al.* (2017) (see **Figure 3.2**).

Figure 3.1. The double Big Bubble Curtain in artist's impression (top; source Wikimedia Commons) and actual deployment (bottom; source Hydrotechnik Lübeck).

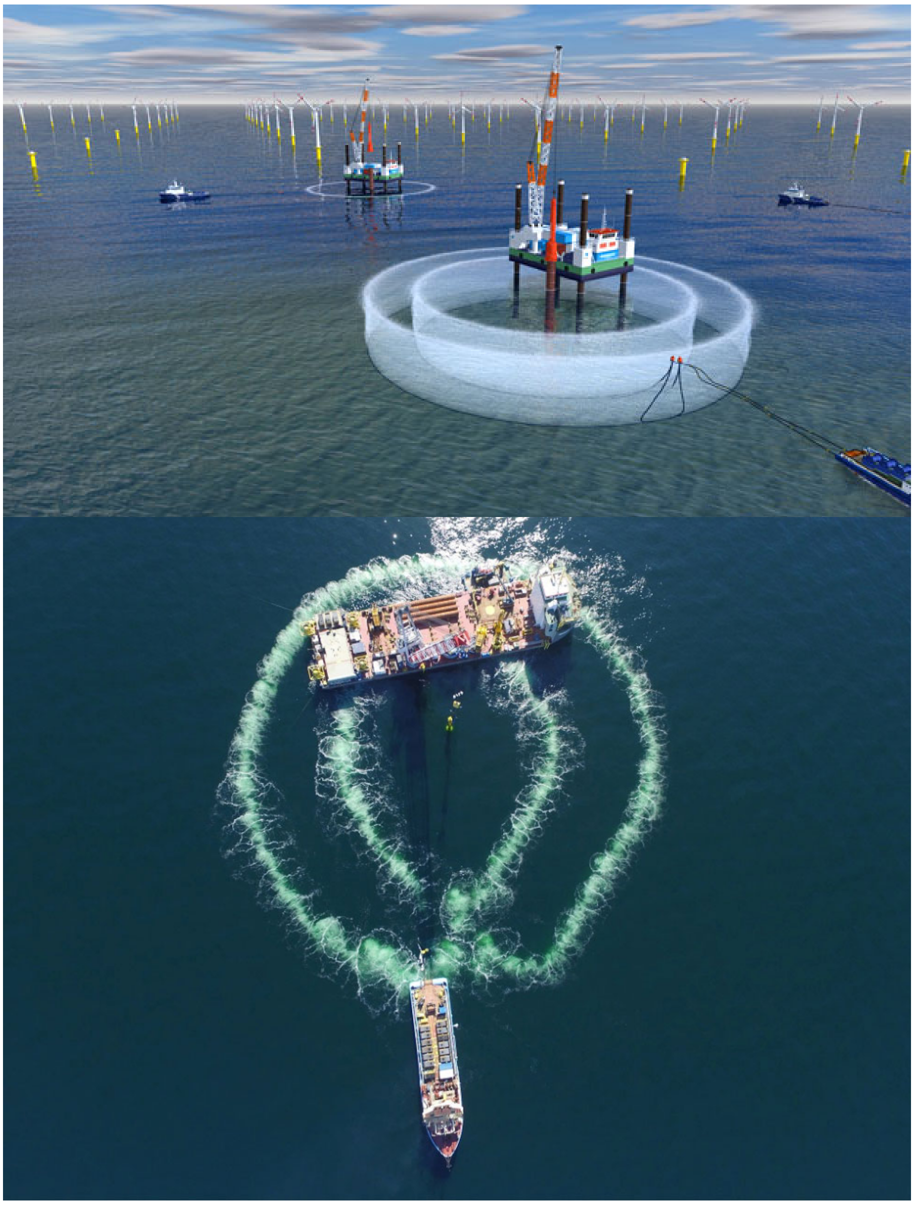
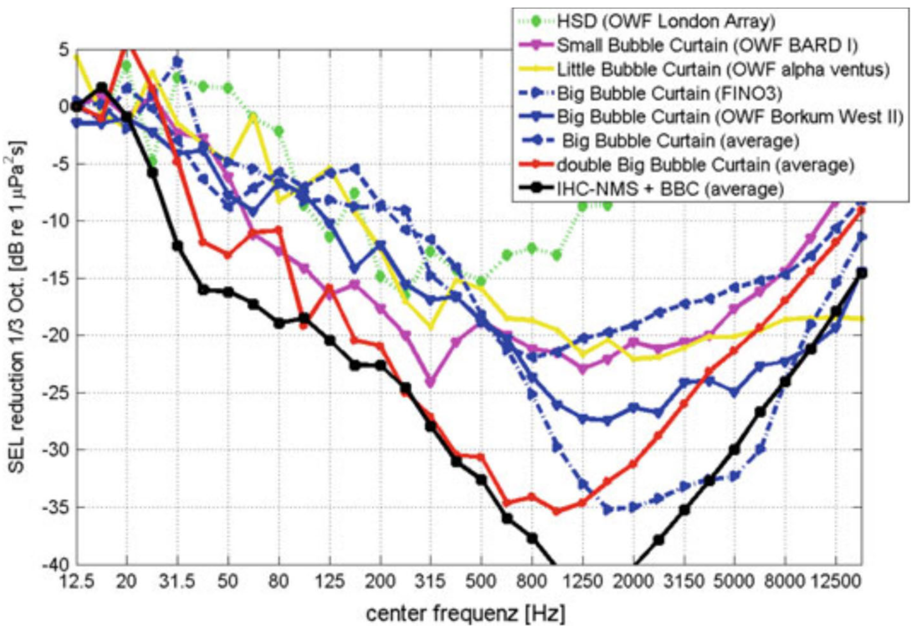


Figure 3.2. Attenuation of pile driving noise by a number of different noise abatement systems. From Bellmann et al. (2017).



3.2 Acoustic deterrence

A key mitigation measure for preventing injury (hearing loss) to marine mammals from pile driving is to deter animals acoustically prior to start of pile driving. This can be done by two methods, often used in conjunction. The first method is deployment of acoustic deterrence devices (ADDs), capable of displacing porpoises from the vicinity of the monopile. The second method, used after deployment of the ADD, is a soft start or ramp up of the energy applied by the hammer to the monopile. Such a ramp up is a normal part of a pile driving for technical reasons, but serves the additional purpose of providing a slow increase in acoustic exposure to animals, high enough to deter them from the piling site, but not high enough to harm them.

A commonly used ADD type for mitigation of pile driving noise is the seal scarer from the company Lofitech, Norway, which is known to be able to deter porpoises out to distances of many kilometers (Brandt *et al.* 2012, Dähne et al. 2017). However, the deterrence at larger distances is not complete (Dähne et al. 2013) and it is thus important to know the maximal distance at which all porpoises with good confidence can be assumed to be deterred, i.e. the extent of the zone where no porpoises are found when pile driving starts. Based on review of available data this distance was conservatively assessed to be 1,300 m for porpoises (Hermannsen *et al.* 2015) and 200 m for seals (Mikkelsen *et al.* 2015).

The downside to using an ADD to deter porpoises prior to pile driving is that this deterrence constitutes a disturbance in itself. There is thus a trade-off between mitigating one impact (damage to the hearing system) and creating another impact (disturbance of behaviour). As noise abatement systems becomes more and more efficient, this trade-off becomes increasingly important and there are indications that the disturbance of behaviour from the ADD may exceed the disturbance caused by the pile driving itself when efficient noise abatement systems are used (Dähne et al. 2017). See further discussion of this issue in the context of Krieger's Flak in section 7.4 below.

4. Acoustic modelling

Modelling of sound propagation from different piling scenarios at Krieger's Flak were modelled by the software package dBSea (Pedersen & Keane 2016). The fundamental model setup, including bathymetry, hydrography and sediment layers, was identical to the modelling done in Tougaard and Mikaelsen (2018). Only a single position was modelled: UTM33 E 377000 N 6108000. This position was considered worst case, due to its location immediately adjacent to the Natura2000 area Sydvästskånes Udsjövatten and in deep water, which facilitates sound propagation.

The parameters changed for the present modelling were related to source spectra and source levels, because of changes to the modelled monopile diameter, and the effectiveness of the noise abatement system, as information about an improved double Big Bubble Curtain could be used.

Source level for the 11 m and 12 m diameter monopiles were extrapolated from measurements on smaller diameter piles (**Figure 4.1**) in the same way as in Tougaard and Mikaelsen (2018).

As frequency spectrum of the pile driving noise without noise abatement system was used the generic spectrum provided by Nehls and Bellmann (2016) (**Figure 4.2**).

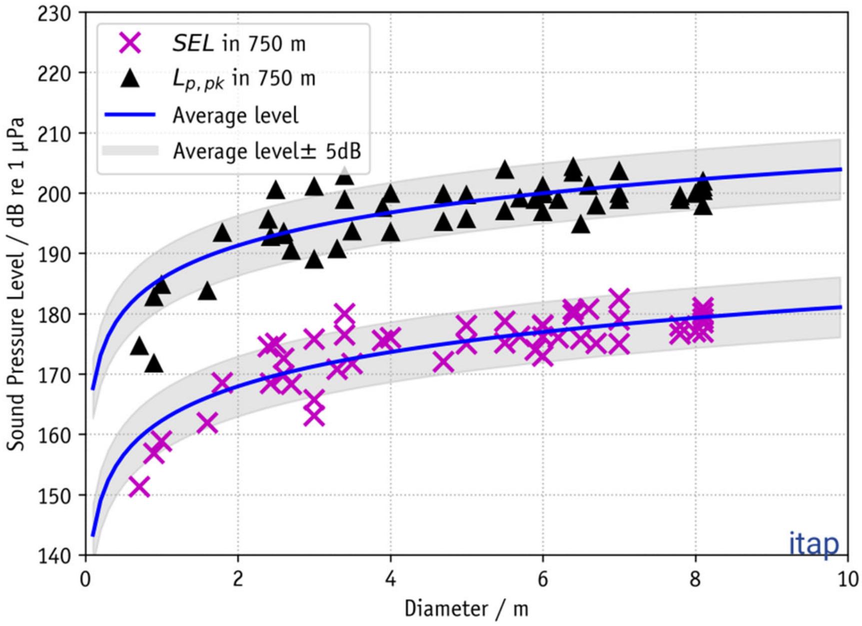
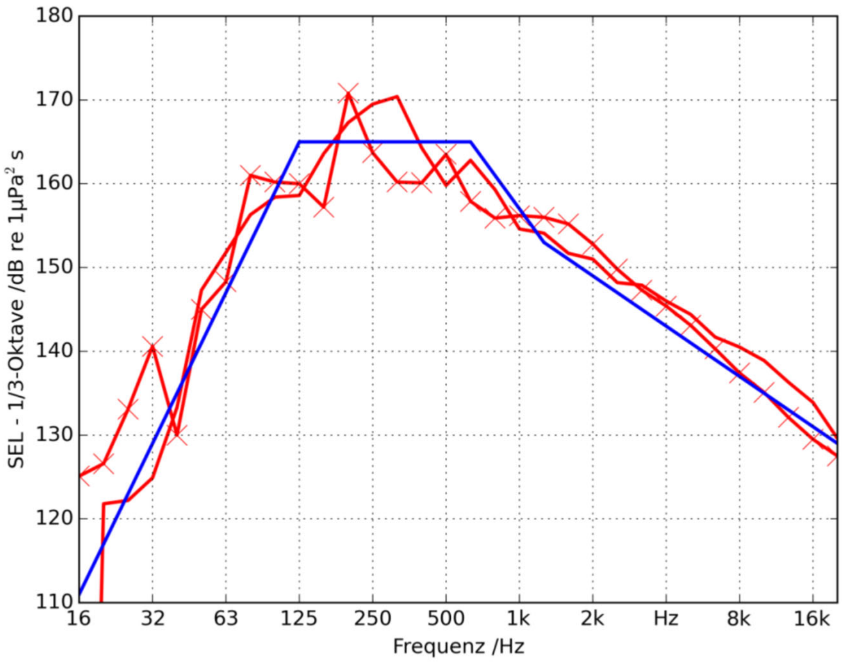


Figure 4.1. Measurements of single pulse sound exposure level at 750 m distance from piling of monopiles without noise abatement system in operation (crosses) and extrapolation to larger diameters (blue lines). Included is also the peak sound pressure level (triangles), not used in this modelling. From Koschinski and Lüdemann (2019)

Input parameters to the sound propagation model in dBSea and the regression parameters for the worst-case sound transmission scenario used in the calculation of cumulated sound exposure levels (see Tougaard & Mikaelsen 2018) are given in **Table 4.1**. The regression parameters are the two parameters κ and α of the simplified transmission loss equation:

$$TL(r) = \kappa \log_{10} r + \alpha r$$

Figure 4.2. Generic source spectrum of pile driving noise used for sound propagation modelling (blue line) and actual measurements (red line with crosses) (Global Tech I offshore wind farm). From Nehls and Bellmann (2016).



Included in the table is also the single pulse SEL predicted in 750 m from the monopile for the different conditions. These values can be used as references for measured values in 750 m's distance. As long as the measured values during actual pile driving do not exceed the levels in the table, the predicted impact on porpoises and seals can be considered to be at or below the estimates given in this assessment.

Table 4.1. Input parameters for the modelling in dBSea and the results of the modelling in the form of the best fitting regression lines to the worst-case transmission loss curves. Right-most column contains the corresponding maximum single pulse SEL in 750 m's distance from the monopile, which can be used for on-site control of the effectiveness of the noise abatement system. dBBC: double Big Bubble Curtain.

Pile diameter	Max hammer energy (kJ)	Mitigation	Frequency weighting	Source level [dB re. 1µPa²s]	Slope (κ) [dB per decade]	Absorption (α) [dB per km]	Single pulse SEL in 750 m [dB re. 1µPa²s]
11 m	4000	None	Porpoise	186.2	14.86	0.51	143.1
			Seal	210.1	15.11	0.29	166.4
		dBBC	Porpoise	174.3	14.80	1.50	130.6
			Seal	184.5	14.40	0.30	142.9
12 m	6000	None	Porpoise	186.9	14.86	0.51	143.8
			Seal	210.8	15.11	0.29	167.1
		dBBC	Porpoise	186.9	14.86	0.51	131.2
			Seal	185.2	14.40	0.30	143.6

The only differences between the 11 m and 12 m monopile scenarios is the hammer energy, which results in slightly higher source levels (less than 1 dB) for the 12 m diameter monopile. The regression parameters for the best fitting models are identical for the two different pile diameters (but varies with mitigation), as the sound propagation properties are unaffected by the source level.

5. Assessment of hearing loss

Assessment of risk of injury, in the form of permanent hearing damage (PTS) to porpoises, was modelled and assessed in the same way as in the previous assessment (Tougaard & Mikaelsen 2018). The only change in assessment is thus the choice of input parameters for the pile driving itself (pile diameter and installation scenario) and mitigation (application of double air bubble curtain, see section 4 above).

Cumulated sound exposure level (SEL), weighted by the appropriate auditory weighting function (National Marine Fisheries Service 2016, Southall et al. 2019), were modelled for two pile diameters, 11 and 12 m, respectively, and for two different scenarios for hammer energy. Both scenarios consisted of a gradual ramp-up phase with 15 strikes / minute and increasing hammer energy, up to a maximum of 4000 kJ / strike and 6000 kJ / strike for 11 and 12 m piles, respectively. After the 30-minute ramp-up phase, piling was modelled at maximum hammer energy and 30 strikes / minute for the remaining 4 hours and 6 hours, respectively.

In calculations of cumulated sound exposure level, it was assumed that no porpoises would be present closer than 1,300 m from the piling site at the beginning of soft start (Hermannsen et al. 2015), assumed to be achieved by deployment of a seal scarer or other deterrent device prior to soft start. Commonly used types of seal scarers are known to affect porpoises at distances of many kilometers (Brandt et al. 2012, Dähne et al. 2017, Mikkelsen *et al.* 2017) and the assumption of a 1,300 m exclusion zone is thus very precautionary (see note on disturbance in section 7.4 below, however). Once soft start commences, it was assumed that the porpoises would swim directly away from the piling site with an average swimming speed of 1.5 m / s (Tougaard & Mikaelsen 2018).

Results of the modelling of the two different pile diameter sizes, with and without employment of a double Big Bubble Curtain (dBBC) are shown in Figure 5.1 and Figure 5.2 and the cumulated sound exposure level (SELcum) given in Table 5.1. In Table 5.1 are also given the corresponding values for seals.

Table 5.1. Worst-case estimates of the cumulated sound exposure level (SEL, dB re 1μPa^{2}s) experienced by porpoises and seals.

Pile diameter	SEL without sound dampening		SEL with dBBC	
	Porpoise	Seal	Porpoise	Seal
11 m	161.6	188.6	145.4	166.3
12 m	162.4	189.4	146.4	167.6

For both pile diameters the cumulated SEL by the end of the piling are almost 10 dB below the PTS-threshold for porpoises (see section 2.2 above), given that the double Big Bubble Curtain is used, indicating that it is unlikely that any porpoises will suffer permanent damage to their hearing as a result of the piling, if a double big bubble curtain or equivalently efficient sound abatement system is used. For seals, the cumulated SEL is more than 10 dB below the threshold for PTS, given that the double Big Bubble Curtain is used.

Figure 5.1. Results of the modelling of cumulated sound exposure level in a porpoise exposed to noise from pile driving of an 11 meter diameter monopile. The porpoise was assumed to be 1,300 m from the monopile at the start of the pile driving and then swimming directly away from the noise source with a speed of 1.5 m/s. Results are shown from two different scenarios, one without noise abatement system (blue) and one with a double Big Bubble Curtain (dBBC, red). Top panel shows the development in hammer energy over the 4.5 hour long pile driving, with a gradual ramp up of energy over the first 30 minutes. Second panel shows the porpoise's distance from the monopile. Third panel shows the single pulse Sound Exposure Level (in dB re. 1 μPa^{2}s VHF-weighted) for each pile driving stroke. Bottom panel shows the increase in cumulated Sound Exposure Level over the course of the pile driving. Note that the time axis in the two bottom figures has been truncated to emphasise the details in the beginning of the pile driving.

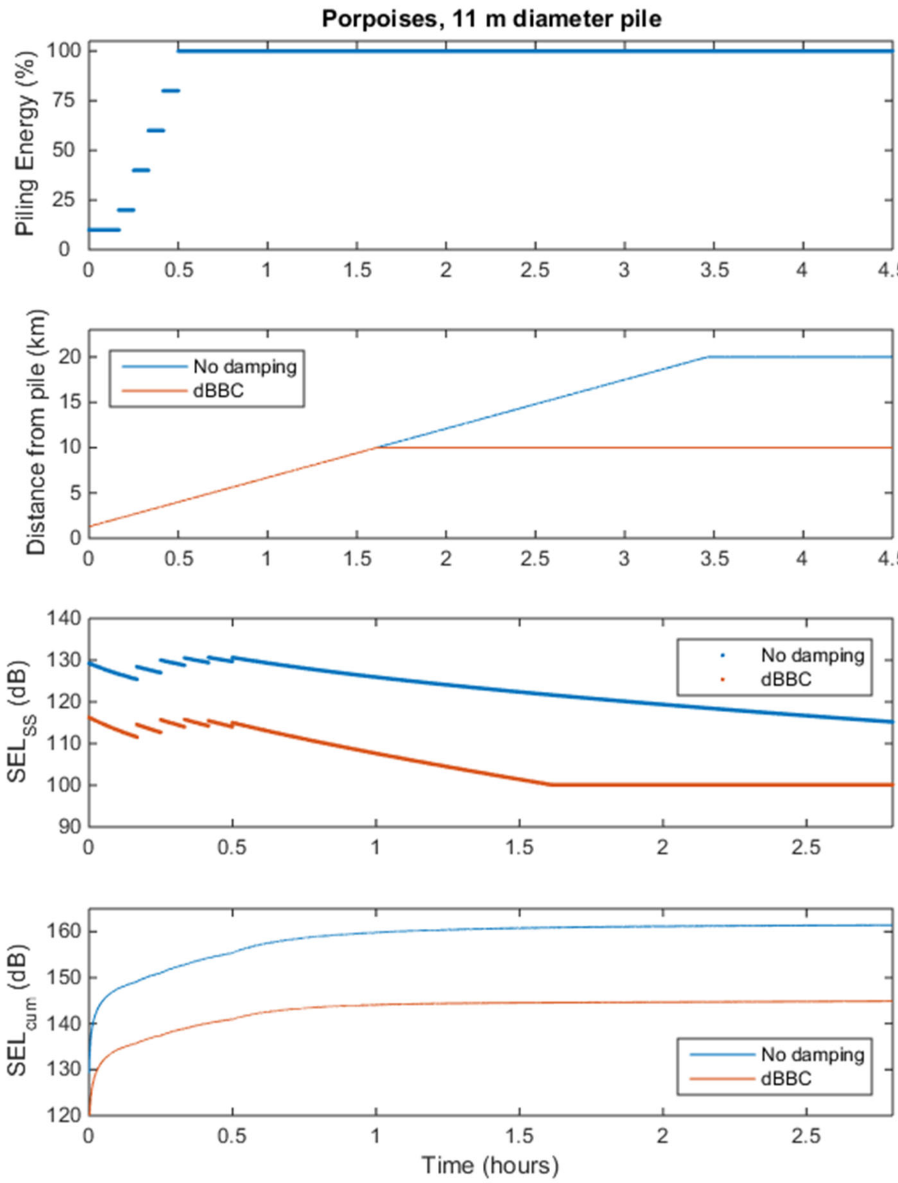
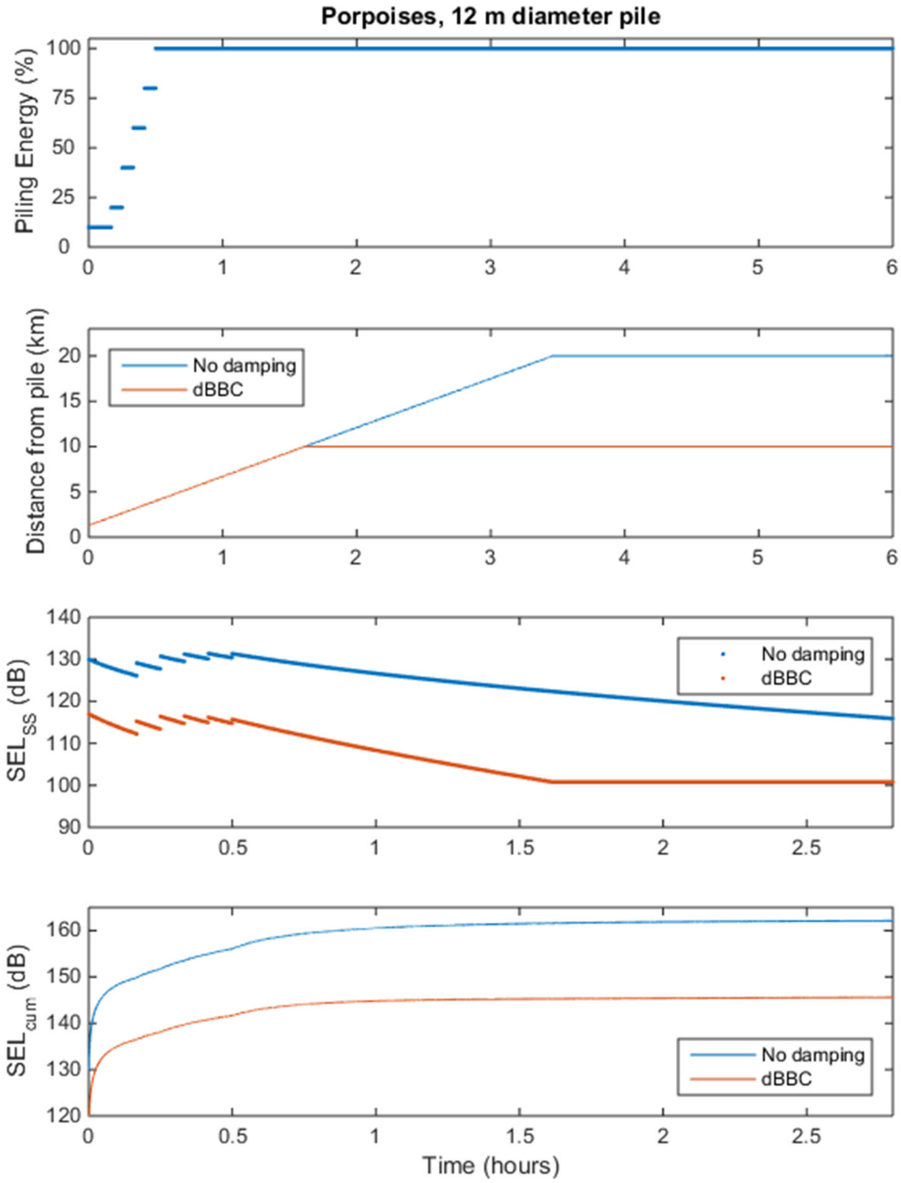


Figure 5.2. Same as **Figure 5.1**, except for a 12 m monopile. Note that the duration of the pile driving is 6 hours, in contrast to 4.5 hours for an 11 m monopile.



6. Assessment of behavioural disturbance

Maps of modelling of the sound pressure level caused by pile driving at Krieger's Flak with the use of a double Big Bubble Curtain are shown in **Figure 6.1** and **Figure 6.2**. The shielding effect of the reef to the south-west is evident, as the sound propagates further towards the deeper waters to the north. There is very little difference between the results from modelling of the two different pile diameters.

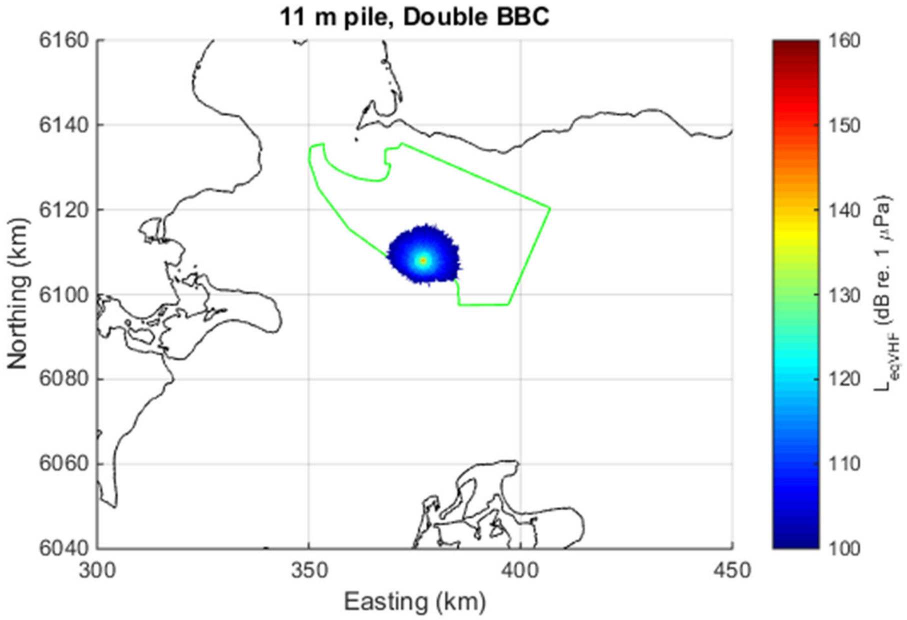


Figure 6.1. Modelled sound pressure level (VHF-weighted) caused by piling of an 11 m diameter monopile with a hammer energy of 4000 kJ per stroke and with use of a double Big Bubble Curtain sound abatement system. Green polygon shows Natura2000 site Sydvästskånes Utsjövatten.

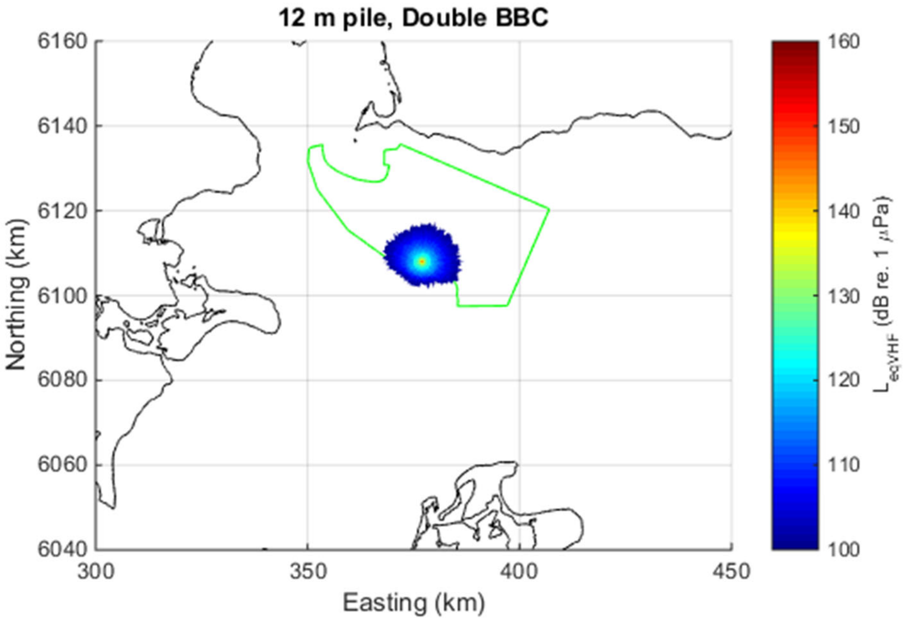


Figure 6.2. Modelled sound pressure level (VHF-weighted) caused by piling of a 12 m diameter monopile with a hammer energy of 6000 kJ per stroke and with use of a double Big Bubble Curtain sound abatement system. Green polygon shows Natura2000 site Sydvästskånes Utsjövatten.

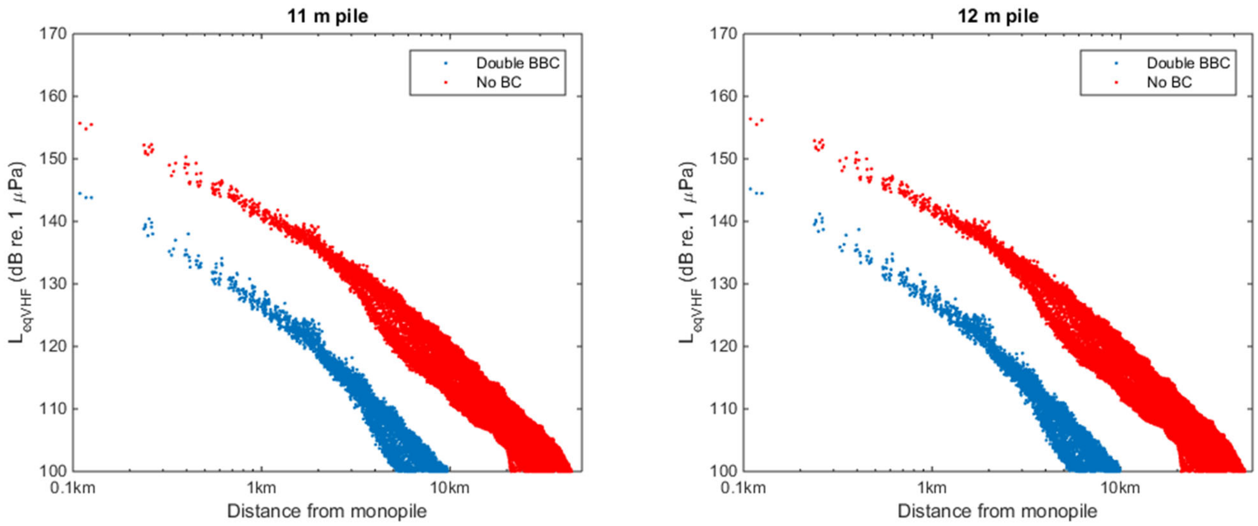


Figure 6.3. Modelled Sound Pressure Level as a function of distance from the piling site for the two different pile diameters (left and right subplot). Both subplots show sound levels with and without a double Big Bubble Curtain sound abatement system (blue and red, respectively). The blue points correspond to the shown data in the maps in **Figure 6.1** and **Figure 6.2**.

Figure 6.3 shows the modelled Sound Pressure Level with distance from pile driving site, also for the case without sound abatement system. Bottom of the y-axis is set to 100 dB re 1 µPa, VHF-weighted, corresponding to the threshold adopted for behavioural disturbance of porpoises (from section 2.3 above) and the curves thus gives an impression of the range at which behavioural effects can be expected. For both pile diameters, the maximum impact range is just under 10 km when a double Big Bubble Curtain or an equivalent noise abatement system is used, whereas the impact range is significantly larger, up to and possibly beyond 50 km for the unmitigated piling. The unmitigated results are somewhat underestimated, as the impact zone extended beyond the modelled area and are included as reference only.

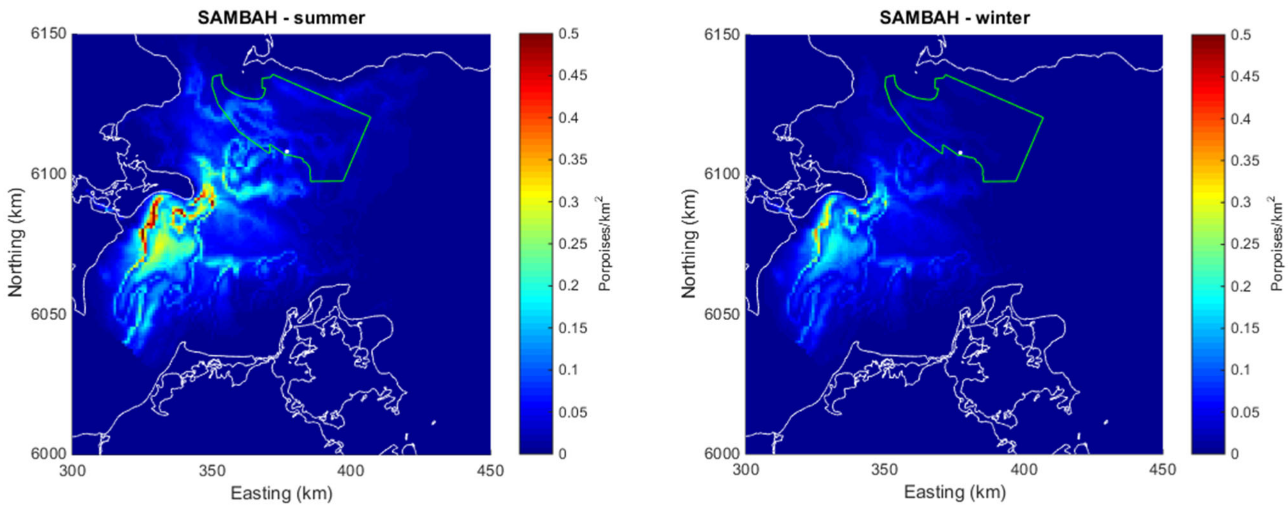


Figure 6.4. Spatial model prediction of the density of porpoises in the waters around Kriegers Flak based on static acoustic monitoring data within the SAMBAH project. Green polygons indicate Sydvästskånes Udsjövatten Natura2000 area and white dots indicate the position of the modelled turbine site. Left map covers summer months (May-Oct), right map covers winter months (Nov-Apr). Data from Carlén et al. (2018).

The abundance of harbour porpoises in the Baltic Sea was modelled within the SAMBAH project (Carlén et al. 2018) and maps are shown in **Figure 6.4**, for summer (May-Oct) and winter months (Nov-Apr). These density surfaces were interpolated to the spatial grid used for sound modelling, by which the average number of disturbed porpoises could be found by summing over all modelled grid cells:

$$N_{disturbed} = \sum Above_{i,j} \cdot D_{i,j} \cdot A_{i,j}$$

where $Above_{i,j}$ is a binary variable, which is 1, if the weighted sound pressure level in cell i,j is above the response threshold (100 dB re. 1 µPa) and otherwise is zero; $D_{i,j}$ is the SAMBAH modelled density of porpoises in the grid cell i,j; and $A_{i,j}$ is the area of the grid cell (=0.0252 km^2).

The area and maximal extent of the zone within porpoise behaviour is predicted to be affected by the pile driving noise is shown in **Table 6.1**. The number of animals predicted to be affected for the four different scenarios (two pile diameters, with or without bubble curtains) modelled are also listed. Affected animals are tallied in total and inside Sydvästskånes Udsjövatten N2000 area. It is immediately clear that there is very little difference between the two pile diameter scenarios, whereas the effect of a sound abatement system is pronounced, with a more than 10-fold reduction in both the impacted area and number of affected individuals.

Table 6.1. Spatial extent of the zone where behavioural disturbance can be expected around pile driving of 11 m and 12 m diameter monopiles, both without sound abatement system and with a system equivalent to the double Bib Bubble Curtain system. Number of impacted animals estimated by combination with the porpoise density surfaces in Figure 6.4.

Mitigation	Pile diameter (m)	Impact area (km^2)	Maximum reaction distance (km)	Impacted porpoises summer[2] (Total/N2000)	Impacted porpoises winter[2] (total/N2000)
None	11	3300[1]	44[1]	158[1]/44	54[1]/11
	12	3500[1]	45[1]	168[1]/44	58[1]/11
Double BBC	11	190	9.7	11/7	3/2
	12	210	9.9	12/8	4/2

[1]Underestimated, as the impact area extended somewhat beyond the modelled area.
[2]Rounded up to nearest integer.

7. Discussion and conclusion

Pile driving, without noise abatement systems, are known to have strong impacts on harbour porpoises and seals, with effects extending out in tens of km's from the piling site. Modelling of the risk of hearing damage, in the form of permanent threshold shift (PTS), confirmed the previous results of Tougaard and Mikaelsen (2018), indicating that both porpoises and seals are likely to be exposed to levels high enough to cause harm to their hearing, even with the use of an effective deterrence device prior to pile driving. Estimates of the zone where behaviour of porpoises can be affected likewise shows that this zone extends very far from the piling site, perhaps as far at 50 km, which extends far beyond the 20-30 km reported from the North Sea (Dähne et al. 2013).

7.1 Effects on porpoises

Modelling of the cumulated sound exposure level and the sound pressure level demonstrate that a noise abatement system with the same (or better) efficiency as the double Big Bubble Curtain can be very efficient and reduce the impact of the pile driving considerably. The use of an appropriate noise abatement system thus eliminates the risk that porpoises will be exposed to sound exposure levels high enough to inflict permanent hearing loss, provided that they are deterred out of a safety zone of the monopile prior to start of pile driving (see, however, note on choice of deterring device in section 7.4 below).

The results further show that the zone of behavioural disturbance for porpoises is reduced by a factor of more than 10, when an adequate noise abatement system is used. When combined with the predicted densities of porpoises it is seen that the number of affected animals, in particular during winter months, is very low: 3 and 4 for 11m and 12 m monopiles, respectively. About half of these animals are predicted to be inside the Natura2000 area for the worst-case shown, where the piling site is very close to the border of the nearby Natura2000 site.

The porpoises in the waters around Krieger's Flak belong to two different populations (See details in Tougaard & Mikaelsen 2018). By far the most of these porpoises belong to the Danish Belt Seas population, whereas a smaller number, in particular during winter months (defined as November through April), are from the critically endangered population from the Baltic Proper (Amundin 2016, Carlén et al. 2018). As the absolute number of porpoises disturbed by the piling noise is very low (when noise abatement systems are used) and the disturbance itself is likely to be small (lasting significantly less than 24 hours)(Brandt *et al.* 2018) the impact of construction of Krieger's Flak offshore wind farm on the Danish Belt Seas population, which is considered to be in favourable conservation status, is assessed to be minor. Likewise, especially due to the very low absolute number of animals disturbed, the impact on porpoises in the nearby Natura2000 site Sydvästskånes Udsjövatten is assessed to be minor and without consequences for the integrity of the site.

Porpoises from the critically endangered Baltic Proper population are likely to be found in the impacted area, especially during winter months (Carlén et al. 2018). However, as this population is estimated to be very small, the proportion of porpoises in the waters around Krieger's Flak that belongs to the Baltic Proper population is expected to be very low. If this is combined with the already very low number of porpoises disturbed by a single pile driving (3-4 animals) and the short duration of the disturbance (around 6 hours), the combined impact on the Baltic Proper population is assessed to be minor and without consequences for the short-term and long-term status of the population. This assessment is under the assumption that an adequate noise abatement system is used (see section 7.5 below).

7.1.1 TTS in porpoises

The cumulated sound exposure level experienced by a porpoise located 1300 m from the piling site at onset of piling (the minimum distance used in modelling) exceeds the threshold for inducing temporary threshold shift (TTS) in porpoises with 5-7 dB. This means that such a porpoise is likely to experience a small amount of TTS, estimated to be 15-20 dB, using the most precautionary slope for predicting TTS (3 dB TTS / / 1 dB noise; Figure 4.4 in Tougaard & Mikaelsen 2018). This amount of TTS is almost certainly completely reversible (Ryan et al. 2016) and normal hearing will be reached within 1-2 hours or less (Popov et al. 2011). Because the TTS furthermore will be at frequencies below 10 kHz (Kastelein et al. 2015) and thus not affect echolocation or mother-calf communication, this is assessed to represent a negligible impact on the porpoise, as it is unlikely to have any significant impact on survival and reproduction success.

7.2 Effects on seals

As noted in section 2 above, there is a lack of quantitative information about reaction distances and abundance of both harbour seals and grey seals, which precludes detailed estimates of the impact. However, several factors point in the direction that at worst, the impact on seals could not be larger than the impact on porpoises:

- Cumulated SEL, appropriately weighted for seal hearing, are well below the threshold for PTS, when a double Big Bubble Curtain is used, as for porpoises.

- Seals are generally considered less reactive to noise than porpoises (Blackwell *et al.* 2004, Mikkelsen et al. 2017), and although some studies indicate that they react as far away from pile driving noise as porpoises do (Russell et al. 2016), there are no indications that they are more responsive to noise than porpoises.

- The grey seals in the waters around Krieger's Flak belong to a common Baltic population and although Krieger's Flak is located at the westernmost edge of their distribution range, the population as a whole is growing and expanding in range. Small disturbances to the grey seals around Krieger's Flak is therefore unlikely to have a noticeable effect on the population.

- Harbour seals around Krieger's Flak belong to the Western Baltic subpopulation, which numbers roughly 2000 animals, distributed over the waters west of Bornholm, southern Øresund and Fehmern Belt (Hansen 2018). This population has been steadily growing over the last almost 20 years and small disturbances to the seals in the area is thus assessed to be unlikely to have a noticeable effect on the status of the population.

- Most of the disturbance of seals is likely to occur within the Natura2000 area Sydvästskånes Utsjövatten, but as the seals belong to a common Western Baltic population, the disturbance to the seals in the Natura2000 area is assessed to be minor, due to the short duration of the disturbance and the small proportion of the Natura2000 area impacted.

- The Natura2000 area Falsterbo-Foteviken, which contains a major haulout site for seals, is too far away to be directly impacted by the pile driving.

All in all, the impact on both grey seals and harbour seals from pile driving, with appropriate noise abatement system in operation, is assessed to be minor and without short-term or long-term consequences for the populations.

7.3 Effects of larger turbines on noise during operation

There is very limited data available on the influence of turbine size and power rating on the underwater noise radiated from the foundation during operation. Whereas the mechanical forces operating on gears and generators increase with increasing power rating of the turbine, so does the height of the tower and hence the distance from noise source to the underwater foundation. The single review available (Madsen *et al.* 2006) failed to find a relationship between turbine size and underwater noise. Newer studies on larger turbines (Betke 2014, Thomsen *et al.* 2015) indicate that larger turbines could be somewhat more noisy than smaller ones, although this relationship has not been quantified. Absolute noise levels are likely to be well below levels radiated from larger merchant ships, however (Madsen et al. 2006).

7.4 Deterrence prior to pile driving

The modelling was performed under the assumption that a Lofitek seal scarer is used prior to each pile driving, to guarantee that no porpoises are present within the exclusion zone with a radius of 1,300 m at the time of the first pile driving strike. However, the Lofitek device is known to affect porpoises at very large ranges. Brandt et al. (2012) reported reactions of porpoises at least 7.5 km away from a pile driving operation (with 3-4.7 m diameter monopiles) and Dähne et al. (2017) reported effects at distances of at least 12 km from pile driving of 6 m diameter monopiles. These reaction distances are comparable to the maximum reaction ranges of about 10 km predicted from the pile driving itself (with dBBC) and indicate that the use of seal scarers to prevent hearing damage may in itself constitute a source of disturbance, which should not be ignored. It is worth exploring possibilities for using other deterrent devices, with lower source level and / or higher frequency signals with lower long-range propagation, such that deterrence within a suitable safety zone can be assured, while long-range disturbance is minimized. Modelling of cumulated SEL under otherwise identical assumptions as above further indicate that the extent of the exclusion zone could be lowered from 1,300 m to 200 m, without exceeding the thresholds for permanent hearing loss.

7.5 Documentation of compliance

The predicted effects on seals and porpoises are so small and of a nature which prevents any direct monitoring of the effects during the actual pile driving operations. Deployment of acoustic porpoise detectors (C-PODs or equivalent) may provide general information about presence of animals in the wind farm area and surrounding waters, but may not provide sufficient number of detections to allow statistically robust conclusions on the effects.

It is proposed that compliance with the assumptions of the assessment is documented by recording the underwater noise from the pile driving at a distance of 750 m from the monopile. Together with information about the actual hammer energy delivered to the monopile (equivalent to the top panel in Figure 5.1 and Figure 5.2), the single pulse sound exposure level (SEL), appropriately frequency weighted, can be used to test the validity of the assumptions behind the modelling and hence the assessments. Thus, if the following conditions are met:

- Single pulse SEL, appropriately frequency weighted, does not exceed the corresponding values given in the rightmost column of **Table 4.1**.
- The duration of the ramp-up phase is not shorter than 30 minutes.
- The average stroke rate does not exceed 15 pulses / min for the ramp-up and 30 pulses / min for the main piling
- The total duration of the piling (excluding breaks) does not exceed 4.5 or 6 hours for 11 m and 12 m monopiles, respectively.

It is fair to conclude that the actual impact was not higher than predicted from the precautionary worst-case estimates provided in this report[4]. If one or more of the conditions above are not met, this does not automatically imply that the actual impact exceeded the predicted level. Whether this was the case or not can only be concluded after a more thorough analysis of the noise recordings and the pile driving details.

[4] There are inherently stochastic parameters, most importantly relating to the actual number of porpoises and seals around the piling site at the time of the construction and the actual sound propagation conditions, which cannot be predicted in advance and therefore cannot be accounted for.

8. References

Amundin, M. 2016. SAMBAH Final report LIFE08 NAT/S/000261. Kolmårdens Djurpark AB, Vildmarksvägen, SE-618 92 Kolmården, Sweden. 77 pp.

Bellmann, M., H. Holst and M. Müller. 2014. Offshore-Windpark „DanTysk" Effizienzkontrolle Hydroschallmessungen. Installationen der Gründungsstrukturen (Monopiles) der 80 Windenergieanlagen und der Umspannstation (Jacket) Darstellung sämtlicher Hydroschallmessungen und Evaluation der eingesetzten Schallminderungssysteme. pp.

Bellmann, M. A., J. Schuckenbrock, S. Gündert, M. Müller, H. Holst and P. Remmers. 2017. Is There a State-of-the-Art to Reduce Pile-Driving Noise? Pages 161-172 *Wind Energy and Wildlife Interactions.*

Betke, K. 2014. Underwater construction and operational noise at alpha ventus. Pages 171-180 *Ecological Research at the Offshore Windfarm alpha ventus.*

Blackwell, S. B., J. W. Lawson and M. T. Williams. 2004. Tolerance by ringed seals (*Phoca hispida*) to impact pipe-driving and construction sounds at an oil production island. Journal of the Acoustical Society of America 115:2346-2357.

Brandt, M. J., A. Diederichs, K. Betke and G. Nehls. 2011. Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. Marine Ecology Progress Series 421:205-216.

Brandt, M. J., A. C. Dragon, A. Diederichs, *et al.* 2018. Disturbance of harbour porpoises during construction of the first seven offshore wind farms in Germany. Marine Ecology Progress Series 596:213-232.

Brandt, M. J., C. Höschle, A. Diederichs, K. Betke, R. Matuschek, S. Witte and G. Nehls. 2012. Far-reaching effects of a seal scarer on harbour porpoises, *Phocoena phocoena*. Aquatic Conservation: Marine and Freshwater Ecosystems 23:222-232.

Carlén, I., L. Thomas, J. Carlström, *et al.* 2018. Basin-scale distribution of harbour porpoises in the Baltic Sea provides basis for effective conservation actions. Biological Conservation 226:42-53.

Dähne, M., A. Gilles, K. Lucke, *et al.* 2013. Effects of pile-driving on harbour porpoises (*Phocoena phocoena*) at the first offshore wind farm in Germany. Environmental Research Letters 8:025002.

Dähne, M., J. Tougaard, J. Carstensen, A. Rose and J. Nabe-Nielsen. 2017. Bubble curtains attenuate noise from offshore wind farm construction and reduce temporary habitat loss for harbour porpoises. Marine Ecology Progress Series 580:221-237.

German Federal Ministry for the Environment and Nuclear Safety. 2013. Konzept für den Schutz der Schweinswale vor Schallbelastungen bei der Errichtung von Offshore-Windparks in der deutschen Nordsee (Schallschutzkonzept). https://www.bfn.de/fileadmin/BfN/awz/Dokumente/schallschutzkonzept_BMU.pdf (accessed 2017/03/10). pp.

Hansen, J. W. R. 2018. Marine områder 2016. NOVANA. Aarhus Universitet, DCE – Nationalt Center for Miljø og Energi, 140 s. - Videnskabelig rapport fra DCE - Nationalt Center for Miljø og Energi nr. 253 http://dce2.au.dk/pub/SR253.pdf. pp.

Hermannsen, L., L. Mikkelsen and J. Tougaard. 2015. Review: Effects of seal scarers on harbour porpoises. Research note from DCE - Danish Centre for Environment and Energy. Aarhus University. pp.

Kastelein, R. A., R. Gransier, M. a. T. Marijt and L. Hoek. 2015. Hearing frequency thresholds of harbor porpoises (*Phocoena phocoena*) temporarily affected by played back offshore pile driving sounds. Journal of the Acoustical Society of America 137:556-564.

Kastelein, R. A., L. Helder-Hoek, J. Covi and R. Gransier. 2016. Pile driving playback sounds and temporary threshold shift in harbor porpoises (Phocoena phocoena): Effect of exposure duration. J Acoust Soc Am 139:2842.

Kastelein, R. A., L. Hoek, C. a. F. De Jong and P. J. Wensveen. 2010. The effect of signal duration on the underwater detection thresholds of a harbor porpoise (*Phocoena phocoena*) for single frequency-modulated tonal signals between 0.25 and 160 kHz. Journal of the Acoustical Society of America 128:3211-3222.

Koschinski, S. and K. Lüdemann. 2019. Noise mitigation for the construction of increasingly large offshore wind turbines. Technical options for complying with noise limits. pp.

Madsen, P. T., M. Wahlberg, J. Tougaard, K. Lucke and P. L. Tyack. 2006. Wind turbine underwater noise and marine mammals: Implications of current knowledge and data needs. Marine Ecology Progress Series 309:279-295.

Mikkelsen, L., L. Hermannsen, K. Beedholm, P. T. Madsen and J. Tougaard. 2017. Simulated seal scarer sounds scare porpoises, but not seals: species-specific responses to 12 kHz deterrence sounds. R Soc Open Sci 4:170286.

Mikkelsen, L., L. Hermannsen and J. Tougaard. 2015. Effect of seal scarers on seals. Literature review for the Danish Energy Agency. Aarhus University, DCE. 19 pp.

National Marine Fisheries Service. 2016. Technical guidance for assessing the effects of anthropogenic sound on marine mammal hearing underwater acoustic thresholds for onset of permanent and temporary threshold shifts. NOAA Technical Memorandum NMFS-OPR-55. 178 pp.

Naturhistoriska Riksmuseet. 2019. Yttrande över remiss av ansökan om Natura 2000-tillstånd för vindkraft Sydvästskånes utsjövatten, Kriegers flak. J.No. Dnr 5.1.6-556-2019. Stockholm.

Nehls, G. and M. Bellmann. 2016. Weiterentwicklung und Erprobung des „Großen Blasenschleiers“ zur Minderung der Hydroschallemissionen bei Offshore-Rammarbeiten Förderkennzeichen 0325645A/B/C/D. pp.

Pedersen, R. S. and M. Keane. 2016. Validation of dBSea, underwater noise prediction software. Pile driving focus. Journal of Shipping and Ocean Engineering.

Popov, V. V., A. Y. Supin, D. Wang, K. Wang, L. Dong and S. Wang. 2011. Noise-induced temporary threshold shift and recovery in Yangtze finless porpoises *Neophocaena phocaenoides asiaorientalis*. Journal of the Acoustical Society of America 130:574-584.

Rodkin, R. B. and K. Pommerenck. 2014. Caltrans compendium of underwater sound data from pile driving – 2014 update. Inter.noise Melbourne Australia. pp.

Russell, D. J. F., G. D. Hastie, D. Thompson, *et al.* 2016. Avoidance of wind farms by harbour seals is limited to pile driving activities. Journal of Applied Ecology:1-11.

Ryan, A. F., S. G. Kujawa, T. Hammill, C. Le Prell and J. Kil. 2016. Temporary and permanent noise-induced threshold shifts: A review of basic and clinical observations. Otol Neurotol 37:e271-275.

Skjellerup, P., C. M. Maxon, E. Tarpgaard, *et al.* 2015. Marine mammals and underwater noise in relation to pile driving - report of working group. Energinet.dk. 20 pp.

Southall, B. L., A. E. Bowles, W. T. Ellison, *et al.* 2007. Marine Mammal Noise Exposure Criteria. Aquatic Mammals 33:411-414.

Southall, B. L., J. J. Finneran, C. Reichmuth, *et al.* 2019. Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects. Aquatic Mammals 45:125-232.

Thomsen, F., A. Gill, M. Kosecka, *et al.* 2015. MaRVEN – Environmental Impacts of Noise, Vibrations and Electromagnetic Emissions from Marine Renewable. pp.

Tougaard, J. and K. Beedholm. 2019. Practical implementation of auditory time and frequency weighting in marine bioacoustics. Applied Acoustics 145:137-143.

Tougaard, J., J. Carstensen, J. Teilmann, H. Skov and P. Rasmussen. 2009. Pile driving zone of responsiveness extends beyond 20 km for harbor porpoises (Phocoena phocoena (L.)). Journal of the Acoustical Society of America 126:11-14.

Tougaard, J. and M. Dähne. 2017. Why is auditory frequency weighting so important in regulation of underwater noise? The Journal of the Acoustical Society of America 142:EL415-EL420.

Tougaard, J. and M. A. Mikaelsen. 2018. Effects of larger turbines for the offshore wind farm at Krieger's Flak, Sweden. Assessment of impact on marine mammals. Aarhus University, DCE – Danish Centre for Environment and Energy, 112 pp. Scientific Report No. 286. . pp.

Tougaard, J., A. J. Wright and P. T. Madsen. 2015. Cetacean noise criteria revisited in the light of proposed exposure limits for harbour porpoises. Marine Pollution Bulletin 90:196-208.

EFFECTS OF LARGER TURBINES FOR THE OFFSHORE WIND FARM AT KRIEGER'S FLAK SWEDEN

Addendum with revised and extended assessment of impact on marine mammals

The prior assessment of consequences for marine mammals of construction of an offshore wind farm on Krieger's Flak, Sweden, has been updated. This update was prompted by changes in the specifications of the wind farm, new information on noise abatement systems and improved methods for quantitative assessment of acoustic disturbance to harbour porpoises. Results show that pile driving of monopile foundations at Krieger's Flak is likely to present a significant impact on harbour porpoises, harbour seals and grey seals in the area, if performed without measures to reduce the radiated noise from the piling. If, however, an adequate noise abatement system, such as an air bubble curtain, is used, the predicted impact is reduced to a level, where it is assessed to constitute only minor impact on the marine mammal populations in the area and the nearby NATURA2000 sites.

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