Underwater noise from pile driving

Comparison of German and Danish regulatory frameworks

Scientific note from DCE – Danish Centre for Environment and Energy

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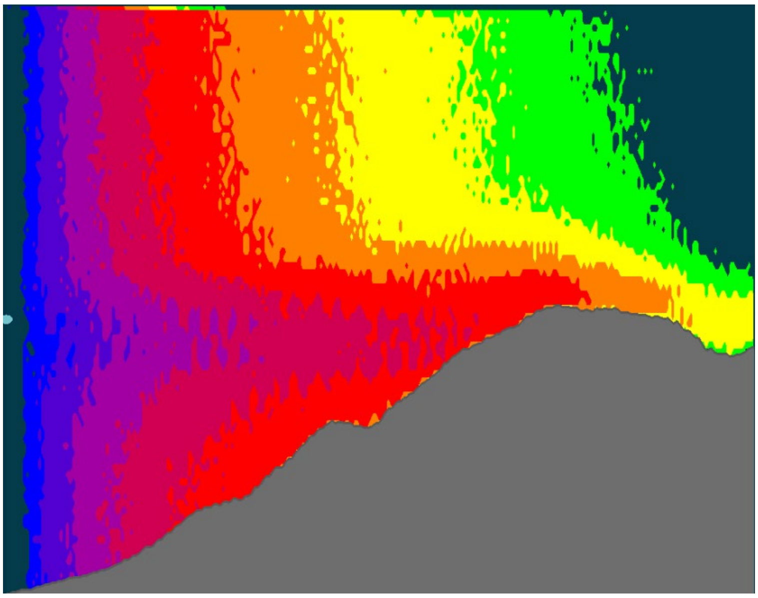

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Data sheet

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Forord

Dette notat indeholder udkastet til et manuskript påtænkt indsendt til tidsskriftet Environmental Impact Assessment Review eller tilsvarende. Manuskriptet er baseret på modelleringer af støjudbredelsen fra en hypotetisk pæleramning med efterfølgende vurdering af behov for afværgeforanstaltninger til beskyttelse af havpattedyr mod høreskader, vurderet i henhold til gældende lovgivning i henholdsvis Tyskland og Danmark. Denne sammenligning er rekvireret af Energistyrelsen som led i forarbejdet til en indsats i henhold til HELCOMs Regional Action Plan for Underwater Noise, der sigter på en regional harmonisering af regulering af undervandsstøj i forbindelse med havvindmøllebyggerier og anden offshore-infrastruktur.

Valg af modelscenarier er foregået i samarbejde med rekvirenten. Lydudbredelsesmodelleringerne er udført af NIRAS A/S. Præsentati-on og diskussion af resultater er lavet i samarbejde mellem Aarhus Universitet, Ecoscience og NIRAS A/S.

Energistyrelsen har haft mulighed for at kommentere en tidligere udgave af manuskriptet.

Manuscript drafted for Environmental Impact Assessment Review

Regulation of underwater noise from pile driving in Denmark and Germany - A side-by-side comparison of regulatory limits to impulsive noise emissions

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Highlights

- Noise emission of a monopile installation was evaluated against Danish and German legislation.
- Differences in regulation caused widely different requirements for noise abatement.
- Highest demand for mitigation was from the German regulatory framework.
- Lower requirements of the Danish guidelines were due to auditory frequency weighting.
- The differences highlight the need for international harmonization of frameworks.

Keywords:

Impulsive noise; offshore wind farm; PTS; marine mammals; harbour porpoise.

Abstract

Underwater noise from pile driving in connection with the construction of offshore wind farms and other maritime infrastructure is very loud and capable of harming marine life. For that rea-son, many countries have legislation in place to regulate noise emissions and mitigate impacts. Two different legislative frameworks were studied and compared side by side: the German Schallschutzkonzept and the Danish Guidelines for pile driving. The requirements for noise abatement of a generic pile driving scenario, by means of a predictive noise prognosis, were evaluated in two set-ups, one in the eastern North Sea and one in the Baltic Sea, both under different hydrographical conditions. Results showed substantial differences between the two legislative frameworks. In all cases, the German noise mitigation concept resulted in highest demand for noise abatement, rooted in the use of unweighted (broadband) noise metrics, in contrast to the Danish guidelines based on auditory frequency weighted noise metrics. For the protection of harbour porpoises, this difference was substantial, up to 13-15 dB. For minke whales and other baleen whales the difference was smaller, up to 4 dB, due to the low frequency hearing of baleen whales. The results highlight the need for a regional harmonization of noise regulation.

1 Introduction

Percussive pile driving is the most common method for installing foundations for offshore wind farms and other offshore infrastructure. This activity – where steel monopiles currently up to 10 m in diameter (XXL monopiles) are hammered into the seabed with a hydraulic hammer – generates very loud sound pressures, capable of injuring and disturbing wildlife at large distances from the piling site (Tougaard *et al.*, 2009; Bailey *et al.*, 2010; Ainslie *et al.*, 2012; Dähne *et al.*, 2013). For this reason, most countries have permitting procedures in place, which includes completion of an environmental impact assessment followed by a requirement for mitigative actions. Although the overall objectives of the different countries' regulations are the same: protection of wildlife against death, injury and excessive disturbance, the specific regulations differ. Differences among countries not only means that developers face different conditions across countries but also that the level of protection for wildlife may differ. Here, we illustrate such differences in both demands for mitigation and protection of marine mammals against injury to their hearing by comparing two rather different regulatory frameworks of Germany and Denmark, respectively.

Effects of pile driving noise on marine mammals

Underwater noise can affect marine mammals in different ways, with direct injury and tissue damage as the most serious effect. Prevention of injury is therefore also the aim of most noise regulations. With the seminal review by Southall *et al.* (2007) a precautionary approach to regulation was proposed. With this approach, the onset of temporary and reversible hearing fatigue, referred to as Temporary Threshold Shift (TTS), is used as a basis for establishing exposure limits for different groups of marine mammals. TTS occurs in mammals, including humans, after exposure to loud noise and is commonly experienced by humans after rock concerts and other loud sound exposures. TTS is reversible – by definition – and the hearing returns to normal after a period of minutes to hours. Louder exposures, resulting in excessive amounts of TTS, are associated with an increasing risk of permanent damage to the hearing – Permanent Threshold Shift (PTS).

The likelihood that TTS or PTS is induced by noise exposure to an animal increase not only with the sound pressure level experienced by the animal but also with the duration of the exposure (Southall *et al.*, 2007; Finneran, 2015; Southall *et al.*, 2019). Thus, the minimum levels for inducing TTS and PTS are expressed as sound exposure level (LE), which is the integral of sound intensity over time:

$$L_E = 10\log_{10}\left(\int_0^T p(t)^2 dt\right) \quad \text{Equation 1}$$

where p is the sound pressure, t is time and T is the duration of the exposure. The unit of L_E then becomes dB re 1 μPa²s.

The frequency spectrum of the fatiguing noise is also important: TTS and PTS can be induced at lower sound exposure levels at frequencies in the range of best hearing of the animal, compared to frequencies outside best range (Finneran, 2015; Tougaard *et al.*, 2015). This is further discussed below in section 1.3 below.

German noise mitigation concept

Germany was the first European country to implement legislation with specific mitigation requirements for pile driving. This was done with the noise mitigation concept (Schallschutskonzept, German Federal Ministry for the Environment and Nuclear Safety, 2013). At the time when the noise mitigation concept was established there was very limited empirical data to support setting of exposure limits. The legislation therefore relies almost exclusively on a single study on harbour porpoises (*Phocoena phocoena*) (Lucke *et al.*, 2009). In this study TTS was induced in a harbour porpoise that was exposed to single noise-pulses from a nearby airgun when the received sound exposure level ($L_{E,SS}$) at the porpoise exceeded 164 dB re 1µPa²s. The corresponding peak pressure (L_p) was 194 dB re 1µPa. Both metrics were calculated on the unweighted (broadband) signals.

The results of Lucke *et al.* (2009) led to the requirement set forward in the noise mitigation concept: during pile driving the received level of single pulses ($L_{E,SS}$) 750 m from the monopile must not exceed 160 dB re 1µPa²s and the peak pressure (L_{peak}) must not exceed 190 dB re 1µPa[1]. These values arose from the results of Lucke *et al.* (2009), with a safety margin subtracted (4 dB). The dual criterion was introduced in line with the dual criterion of Southall et al. (2007) in their noise exposure criteria for marine mammals based on the observation that very loud, but also very short impulses are able to induce TTS at lower received SEL than other sounds. A consensus has been established in application of the noise mitigation concept that the 160 dB re 1µPa2s at 750 m limit applies to the 95th percentile of all pile driving sounds within piling of one monopile, meaning that 5% of the individual pulses are allowed to exceed the limit (Müller and Zerbs, 2011).

What does the noise mitigation concept look like seen from the point of view of a porpoise? In a strict interpretation, if a pile driving event produces noise equivalent to that produced in the experiment by Lucke *et al.* (2009) with a level of exactly 160 dB re 1µPa²s at 750 m from the pile, then porpoises closer than 750 m from the pile are at risk of acquiring TTS from exposure to just a single pile driving pulse. This risk is typically mitigated using acoustic deterrence devices, such as seal scarers, that have proved very efficient in deterring porpoises (e.g. Olesiuk *et al.*, 2002; Mikkelsen *et al.*, 2017; Voß *et al.*, 2023). Porpoises further away than 750 m will not risk TTS from exposure to single pulses but are still at risk from TTS from repeated exposure to multiple pulses due to the cumulative impact across repeated pulses (see for example Kastelein et al., 2015).

Danish guidelines

The first version of the Danish guidelines were based on Skjellerup *et al.* (2015) and Skjellerup and Tougaard (2016) and were recently updated and revised (Danish Energy Agency, 2023; see also Lützen *et al.*, 2023). These guidelines were developed as an alternative to the noise mitigation concept because of a wish to include empirical evidence obtained after Lucke *et al.* (2009) into the scientific justification (as reviewed by Finneran, 2015; Tougaard *et al.*, 2015).

[1] It is ambiguous from the noise mitigation concept whether the pressure limit (190 dB re 1µPa) is a peak level or peak-to-peak level, the latter being roughly 6 dB higher for pile driving signals. The name 'Spitzenschalldruckpegel' indicates the former, whereas the symbol $L_{peak\text{-}peak}$ indicates the latter. There seems to be consensus on an interpretation as a peak level (see for example Bellmann et al. (2020)), i.e. the less restrictive choice.

In brief, the cumulative impact from repeated exposures, together with the movement of animals away from the piling site is handled by selecting a minimum start distance, r_{start} and a speed v_{flee}, with which the animal is expected to flee away from the noise once piling starts. The start distance is the closest that an animal is realistically expected to be to the monopile at the time the pile driving starts, and the recommended value of the guidelines is 200 m. For harbour porpoises the flee speed is assumed to be 1.5 m/s. In this scenario, the noise level received by the animal decreases as the animal moves away from the pile driving. To some degree this is counteracted by the soft start and ramp up typically employed as mitigation, where the hammer energy and hence the source level is gradually increased over the first hour or so of the pile driving.

Figure 1 illustrates the concept of an animal moving away with a steady speed, the received level of individual pile strikes decreasing with time, except for the ramp up period, and the cumulative increase of the exposure over the course of the piling.

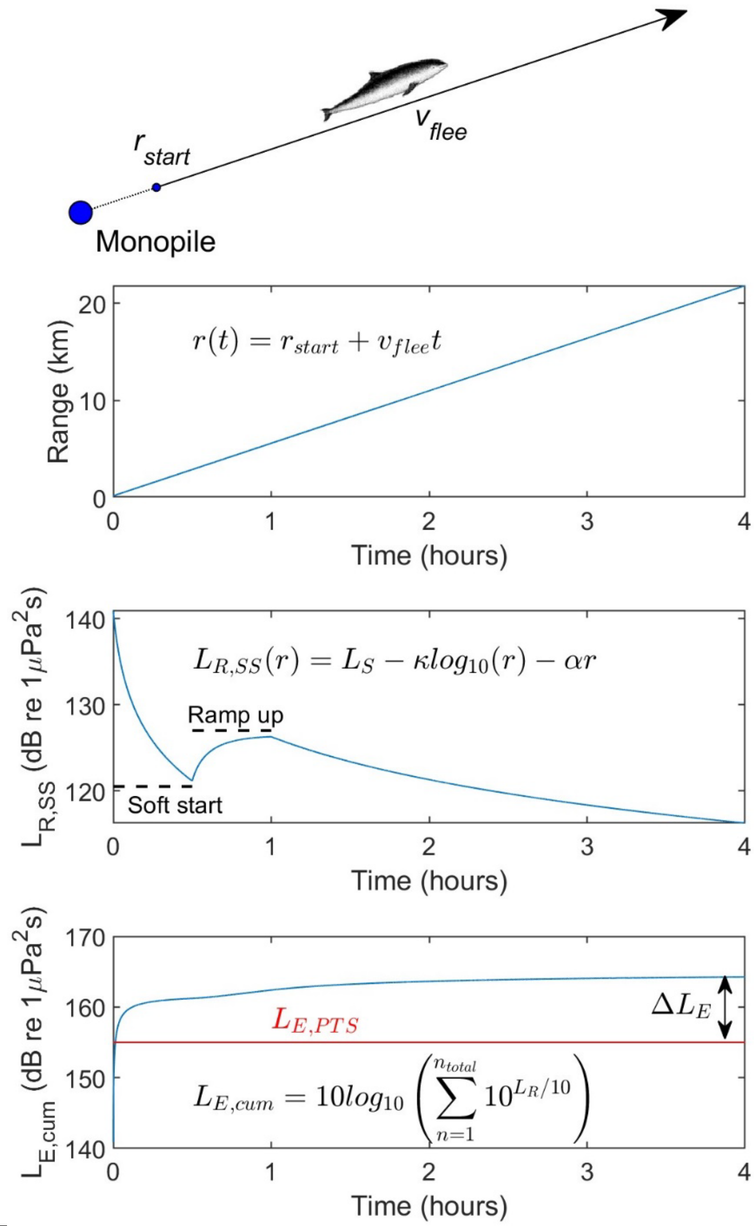

Figure 1. Schematic illustration of the way cumulative sound exposure level ($L_{E,cum}$) is calculated according to the Danish guidelines (Danish Energy Agency, 2023) for a pile driving lasting four hours, of which the first 30 minutes is a soft start, followed by 30 minutes of ramp up to maximum impact energy. Within this period, the frequency weighted $L_{E,cum}$ is calculated for an animal which is at the distance r_{start} (set to 200m) at t=0 and flees with a speed of 1.5 m/s for the duration of the pile driving, and is the sum of the received levels (L_R) of individual pulses received at time t and distance r from the monopile. LR in turn is found from the source level of the monopile noise (L_S) and the simplified equation for the transmission loss, characterized by the parameters κ and α. In this example $L_{E,cum}$ for a porpoise exceeds the PTS onset threshold of 155 dB re 1μPa^{2}s by 10 dB, which means that noise abatement of at least 10 dB (VHF-weighted) is required for the piling to be in accordance with the Danish guidelines.

In contrast to the noise mitigation concept, which operates on broadband sound levels, the Danish guidelines are based on sound exposure levels that are frequency weighted. Auditory frequency weighting refers to the process by which sound levels are adjusted to compensate for the fact that animal hearing is not equally good at all frequencies and hence also the susceptibility to TTS and PTS differs across frequencies. Auditory frequency weighting functions were derived for several functional hearing groups of marine mammals by Southall *et al.* (2019), recently revisited but not revised by Tougaard *et al.* (2022). Four functional hearing groups are considered in the Danish guidelines: very high frequency (VHF) cetaceans (porpoises), high frequency (HF) cetaceans (dolphins and other odontocetes), low frequency (LF) cetaceans (baleen whales) and phocid seals (PCW). The weighting curves for these four groups are shown in Figure 2. PTS onset thresholds, used to determine if and how much mitigative attenuation of the pile driving noise is required, are taken from Southall et al. (2019). In practical application of the weighting functions and the group-specific exposure limits, the appropriate weighting curve is added to the frequency spectrum of the pile driving noise before the $L_{E,cum}$ is calculated. The frequency-weighted $L_{E,cum}$ is then compared to the PTS onset threshold for impulsive noise for the appropriate species group.

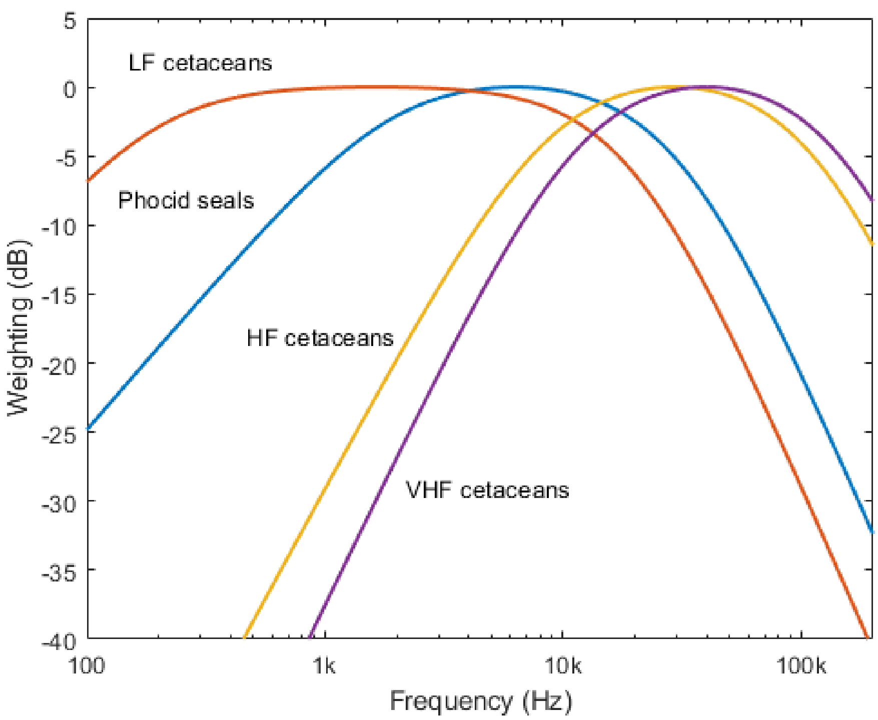

Figure 2. Weighting curves from Southall *et al.* (2019) for the four species-groups mentioned in the Danish guidelines. Except for the LF cetaceans, the curves are based on empirical data on hearing and susceptibility to TTS at different frequencies. A large negative weighting factor is applied to the parts of the frequency spectrum where the species group has poor hearing, and higher received levels therefore are required to elicit TTS/PTS.

Seen from the animals' perspective, a pile driving conducted in a way that just fulfils the requirements of the Danish guidelines means that animals present 200 m or more from the monopile at the start of the pile driving will have sufficient time to flee, such that the cumulative (weighted) SEL experienced by the animal does not exceed the (weighted) threshold for eliciting PTS. This would correspond to a case where the $L_{E,cum}$ curve in Figure 1 (bottom) did not exceed the threshold for PTS (red line).

Mitigation measures

According to both German and Danish regulation, a predictive prognosis of noise exposure must be conducted as part of an environmental impact assessment. If this prognosis shows that exposure limits are likely to be exceeded, mitigation in the form of noise abatement is required. The role of noise abatement is to attenuate the radiated noise sufficiently to remain within the limits of the regulation. Currently, there are a number of noise abatement systems available for large-scale pile driving, such as air bubble curtains or static absorbers/reflectors (see Koschinski and Lüdemann (2020) for a recent review and Bellmann *et al.* (2020) for measures of their efficiency). An example of the attenuation of radiated noise by one type of abatement, an air bubble curtain, is shown in Figure 3.

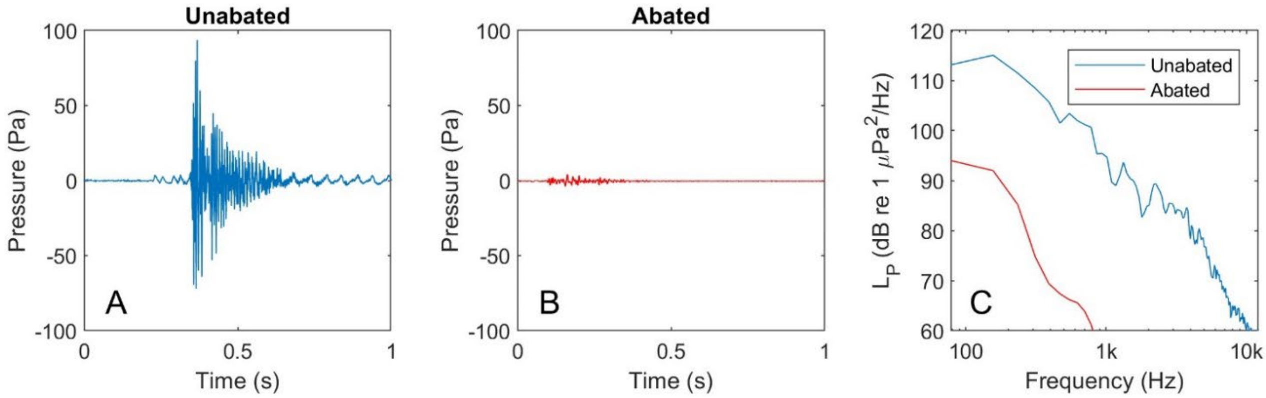

Figure 3. Effect of noise abatement on pile driving noise. A) Single pulse from piling without noise abatement recorded 14 km away. B) Single pulse from piling with a double big bubble curtain recorded 16 km away. C) Power density spectra of the pulses in A) and B), illustrating the substantial reduction in sound pressure level across all frequencies by the noise abatement system. Recordings from construction of the DanTysk offshore wind farm. Additional information can be found in Dähne et al. (2017).

2 Methods

The differences between the German noise mitigation concept and the Danish guidelines were studied by comparing the mitigation measures required under the two regulatory frameworks for the same pile driving scenario. Several predictive noise prognoses were made based on a generic pile driving scenario, where a 15 m diameter steel monopile is installed in two different geographical locations: the eastern North Sea and the Baltic Sea. A 15 m diameter monopile is significantly larger than the largest piles installed today but is representative of the pile sizes anticipated for the future wind farms currently under planning (e.g. Tougaard *et al.*, 2021). The output of the acoustic propagation models was then evaluated against German and Danish requirements, which resulted in specific demands for noise abatement in order to adhere to the two different regulatory frameworks.

2.1 Modelling of acoustic prognosis

Source level and spectrum for the 15 m monopile pile driving noise was based on a back-calculation from measurements in the German North Sea, made 750 m from the monopile (Bellmann *et al.*, 2020; figure 13 and 14), with a source level, $L_{S,E} = 228.2 dB\ re.$ 1 µPa² m² s. The source level was extrapolated from the trend for smaller diameter monopiles (up to 8 m; Bellmann *et al.*, 2020, figure 12). No frequency shifting of the spectrum was performed to compensate for the larger pile, and no site-specific compensation of source level was carried out. A theoretical piling procedure with a 30-minute soft start (1200 pile strikes at 20% hammer energy), a 30-minute ramp up from 20% - 80% hammer energy (1200 pile strikes) and a 180-minute full power phase (7200 pile strikes) was assumed in all calculations. Sound propagation modelling tool dBSea (Pedersen and Keane, 2016) release 2.4.7 was used to model the sound propagation. A combination of dBSeaNM (normal modes implementation) for frequencies 12.5 Hz - 400 Hz and dBSeaPE (parabolic equation implementation) for frequencies 500 Hz – 32 kHz was used. Modelling took place in decidecade bands with 3x frequency oversampling. The model steps were 50 m over range, 0.5 m over depth, and 45 transects radiating from the source. The resulting output was extracted as the maximum over depth for each range step (50 m) between source and maximum range. Results therefore represent the highest modelled levels at any depth at any distance. The source was modelled as an equivalent point source model, as a single omnidirectional source located in the middle of the water column at each source location.

Two sites were included, intended to be representative of typical conditions in the North Sea and the Baltic Sea. Strictly, the German noise mitigation concept is only valid for the North Sea but was applied to a position in the Baltic Sea as if it was legally applicable. Position 1 (56.3842°N, 7.7222°E; EPSG:4326) was in the eastern part of the Danish North Sea (wind farm development area Thor). Position 2 (54.8929°N, 14.1083°E; EPSG:4326) was at the entrance to the Baltic Proper (wind farm development area Energy Island Bornholm). For both positions, salinity, temperature and sound speed profiles were derived from the Copernicus (2023) dataset, bathymetry was extracted from EMODnet (2022) and seabed substrate for the top soil from EMODnet (2021).

Two hydrographical scenarios were modelled for position 1: summer (August) and late winter (March), based on a choice of the most extreme sound speed profiles. Sound speed data showed iso-velocity profiles throughout 2023, except for June, where downward refracting conditions were present. The sediment model consisted of a 10 m sand layer, with 50 m moraine below. The depth at the modelled piling site was 28 m.

The hydrographical conditions in the Baltic Sea are more variable and complex than in the North Sea and therefore four seasonal scenarios were modelled: February, May, July, and November. The most extreme conditions were present in July (sound speed minimum 10 m above the seabed) and November (strong upward refracting conditions). The sediment model consisted of a 6 m muddy sand layer on top, followed by 16 m moraine and a thick chalk layer in the bottom. The depth at the modelled piling site was 40 m.

2.2 Required attenuation to meet requirements

Modelling results were extracted from dBSea results as $L_{E,SS}$ (maximum over depth) at distance steps from monopile out to a maximum distance of 20 km and for each of the 45 radial transects. This was repeated for each source position and each hydrographical scenario. For each combination, the unweighted $L_{E,SS}$ and the frequency weighted levels for harbour porpoises (VHF cetaceans, $L_{E,SS,VHF}$) and seals (phocid carnivores in water, $L_{E,SS,PCW}$) were extracted. For the North Sea also $L_{E,SS,LF}$ weighted for minke whales (*Balaenoptera acutorostrata,* LF cetaceans) and $L_{E,SS,HF}$ weighted for white-beaked dolphins (*Lagenorhynchus albirostris,* HF cetaceans) were extracted.

Required attenuation ($\Delta L_{E,SS}$) to conform to the noise mitigation concept was calculated for each scenario as the difference between the maximum unweighted $L_{E,SS}$ modeled at 750 m distance and the 160 dB re 1µPa²s limit: $\Delta L_{E,SS} = L_{E,SS,750m} - 160\ [dB\ re\ 1\ \mu Pa^2 s\ ]$. The second German criterion – peak pressure at 750 m not exceeding 190 dB re 1µPa – was not evaluated, as the $L_{E,SS}$ criterion always is the most restrictive criterion for pile driving noise (Bellmann *et al.*, 2020).

Required attenuation according to the Danish guidelines was calculated separately for each of the species-groups. LF and HF cetaceans were not considered for the position in the Baltic Sea, as species belonging to these groups are not commonly present and are not required to be included in assessments (Tougaard *et al.*, 2020). First, a simplified model for sound propagation was made for each scenario and species group, following the Danish guidelines, by fitting parameters κ and α of the equation TL(r) = κlog(r) + αr to obtain best fit to modelled $L_{E,SS}$ values. Second, for each group, the cumulated exposure to an animal present 200 m from the monopile at the start of piling was calculated from equation 2, using a fleeing speed (v_f) of 1.5 m/s.

$$L_{E,cum} = 10 * log_{10}\left(\sum_{i=1}^{N} \frac{S_i}{100\%} * 10^{\left(\frac{L_{S,E} - \kappa * log_{10}(r_{start} + v_f * t_i) - \alpha * (r_{start} + v_f * t_i)}{10}\right)}\right) \quad \text{Equation 2}$$

N is the total number of strikes used to drive one monopile, and S_i is the sequence of hammer energies used in the piling, including soft start and ramp up. Mitigation requirements are then calculated for each species through $\Delta L_{E,sp.group} = L_{E,cum,sp.group} - PTS_{sp.group}$ using the species-group specific PTS onset thresholds) from Southall *et al.* (2019) for LF cetaceans (183 dB re 1µPa²s); HF cetaceans (185 dB re 1µPa²s); VHF cetaceans: (155 dB re 1µPa²s) and phocid seals (185 dB re 1µPa²s.

3 Results

Figure 4 shows the results of modelling the standard scenario without noise abatement in the two different locations. For both locations the month with the largest impact ranges is shown (March and February, respectively). The black contours are the iso-contour for $L_{E,SS}$ = 160 dB re 1 $\mu Pa^2 s$, the limit not to be exceeded 750 m from the monopile according to the noise mitigation concept. These iso-contours are tens of kilometres from the piling sites, indicating that the unabated noise levels are predicted to be far above what is permitted according to the German limit. The red and blue contours show the iso-contours for the closest safe start distance (r_{start}) for porpoises and minke whales (the latter only for the North Sea) according to the Danish guidelines. These contours indicate that an animal inside the contour at the start of the pile driving is predicted to be unable to escape fast enough to avoid exposure above the PTS onset threshold for the species and therefore at risk of acquiring permanent damage to their hearing. To be in accordance with the Danish guidelines, r_{start} must be 200 m or less. For minke whales r_{start} was more than 40 km, for porpoises a few km in the North Sea and more than 10 km in the Baltic (depending on direction away from the piling site). As in the case for application of the noise mitigation concept there is a substantial need for noise abatement for the standard scenario to be within limits required in the Danish guidelines. The iso-contour for r_{start} calculated for dolphins (HF-cetaceans) and seals (phocid carnivores) according to the Danish guidelines were too close to the piling site to be visible on the maps.

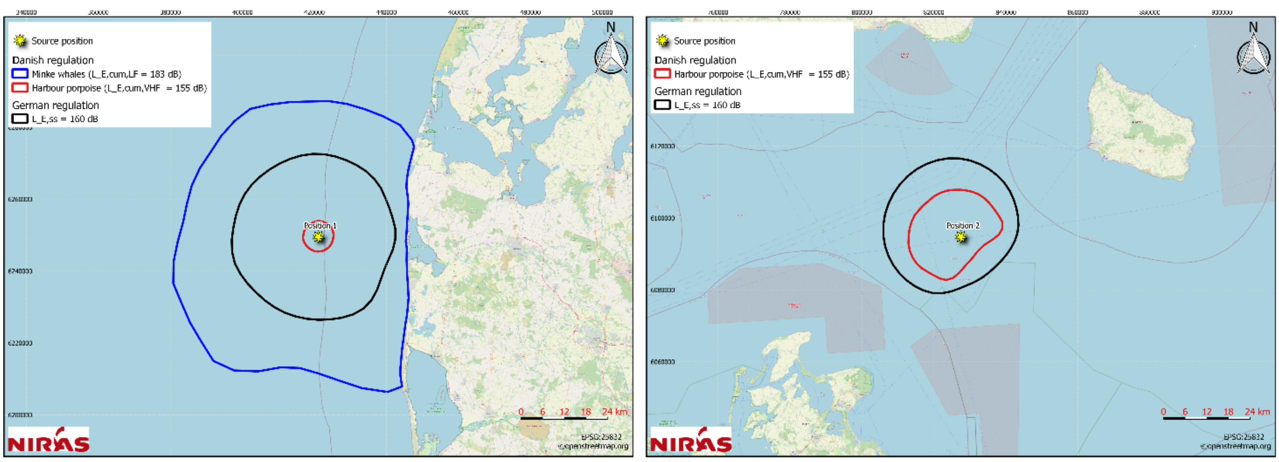

Figure 4. Two examples of modelling of radiated noise from pile driving at the North Sea position (left) and the Baltic Sea position (right). In black is the 160 dB $L_{E,SS}$-unweighted iso-contours. The r_{min} for porpoises is indicated in red and for the North Sea also r_{min} for minke whales (LF-cetaceans) in blue. r_{min} for seals and dolphins were smaller than the porpoise contours in all cases and are not shown. The 750 m contour is smaller than the size of the marker for the monopile (star).

The required attenuation under the different scenarios is listed in Table 1. Application of noise abatement with an attenuation at the indicated level or larger will bring the predicted exposures in all directions down under the respective limits of the German and Danish regulation. Note that the attenuation required to comply with Danish limits are frequency weighted and therefore not directly comparable to the German values. Several points are noteworthy from Table 1. First, even though there were substantial differences in the hydrographical conditions from month to month, in particular in the Baltic Sea (see supplementary material), the variation in required attenuation for the same species at the same location is very small, within 1 dB almost in all cases. Second, there are substantial differences between required attenuation to comply to Danish limits for the four different species-groups. The extremes are in the North Sea, where 24 dB of LF weighted attenuation is required to stay within limits of the guidelines for LF-cetaceans (minke whales), whereas HF-cetaceans (dolphins) are 13 dB below the limit, which means that the source level of the pile driving could be 13 dB higher and predicted exposure to dolphins would still be within permitted limits. Third, there is a substantial difference between required attenuation to remain within German and Danish limits for harbour porpoises.

Table 1. Attenuation required to fulfill criteria according to German and Danish legislation for the standard pile driving scenario modelled in two different locations and for different times of the year. The negative attenuation requirements for dolphins means that the cumulated exposure to a dolphin fleeing from 200 m starting distance was 13 dB below the PTS onset threshold for HF cetaceans. For German regulation, mitigation values refer to unweighted spectra, while Danish regulation mitigation values refer to frequency weighted values, for the different marine mammal species-groups. Therefore, it is only possible to compare absolute values within columns, not across columns. See text for further explanation.

	Month	**German noise mitigation concept** Required attenuation (ΔL_E)	**Danish guidelines** Required attenuation			
			Baleen whales ($\Delta L_{E,LF}$)	Dolphins ($\Delta L_{E,HF}$)	Porpoises ($\Delta L_{E,VHF}$)	Seals ($\Delta L_{E,PCW}$)
North Sea	March	27.5 dB	23.8 dB	-13 dB	11.9 dB	7.6 dB
	August	27.3 dB	23.3 dB	-13.1 dB	12.1 dB	7.0 dB
Baltic Sea	February	25.5 dB*	-	-	9.9 dB	3.7 dB
	May	25.2 dB*	-	-	10 dB	3.3 dB
	July	25.1 dB*	-	-	11.2 dB	3.7 dB
	November	25.4 dB*	-	-	10.3 dB	4.3 dB

*Note: The German noise mitigation concept is not legally binding in the Baltic Sea but treated in the same way as for the North Sea.

The absolute values cannot be compared directly, as the Danish guidelines operate on weighted levels whereas the German noise mitigation concept uses unweighted levels, but it is possible to compare the values to what can currently be achieved with best available abatement technology. Figure 5 shows examples of decidecade[2] spectra of pile driving noise measured with and without noise abatement 750 m from the monopile (data from Bellmann *et al.*, 2020, figure 33). Figure 5A shows unweighted spectra, used to evaluate the realized attenuation (ΔL_E) according to the noise mitigation concept. The attenuation equals the difference between the sum of the spectrum of the unabated noise and the sum of the spectrum of the abated noise:

$$\Delta L_E = 10\log_{10}\left(\sum 10^{L_{p,ddec}(f_i)/10}\right) - 10\log_{10}\left(\sum 10^{L_{p,abated,ddec}(f_i)/10}\right) \qquad \text{Equation 3}$$

In the example the realized unweighted attenuation amounts to 20 dB, not sufficient to fulfill the requirements of the noise mitigation concept (27-28 dB in the North Sea, 25-26 dB in the Baltic Sea, Table 1).

In the same manner the VHF-weighted attenuation can be calculated from the VHF-weighted spectra (Figure 5B). In this case the realized attenuation amounts to 44 dB, more than required to remain within the limit of the Danish guidelines (12 dB in the North Sea, 10-11 dB in the Baltic Sea). The LF-cetacean

[2] Often referred to as one-third octave bands and equal to a bandwidth 1/10 of a decade. Decidecade is the preferred terminology according to ISO18405 (ISO, 2017).

weighted attenuation, applicable to minke whales, amounts to 22 dB, 1-2 dB short of what would be required to remain below the Danish limits (23-24 dB). For seals the realized attenuation (27 dB) is well above the required levels (7-8 dB and 3-4 dB for the North Sea and the Baltic Sea, respectively. Frequency weighted attenuation was not calculated for the HF weighting, applicable to dolphins, as this group was within limits even for the unabated scenario (-13 dB, Table 1).

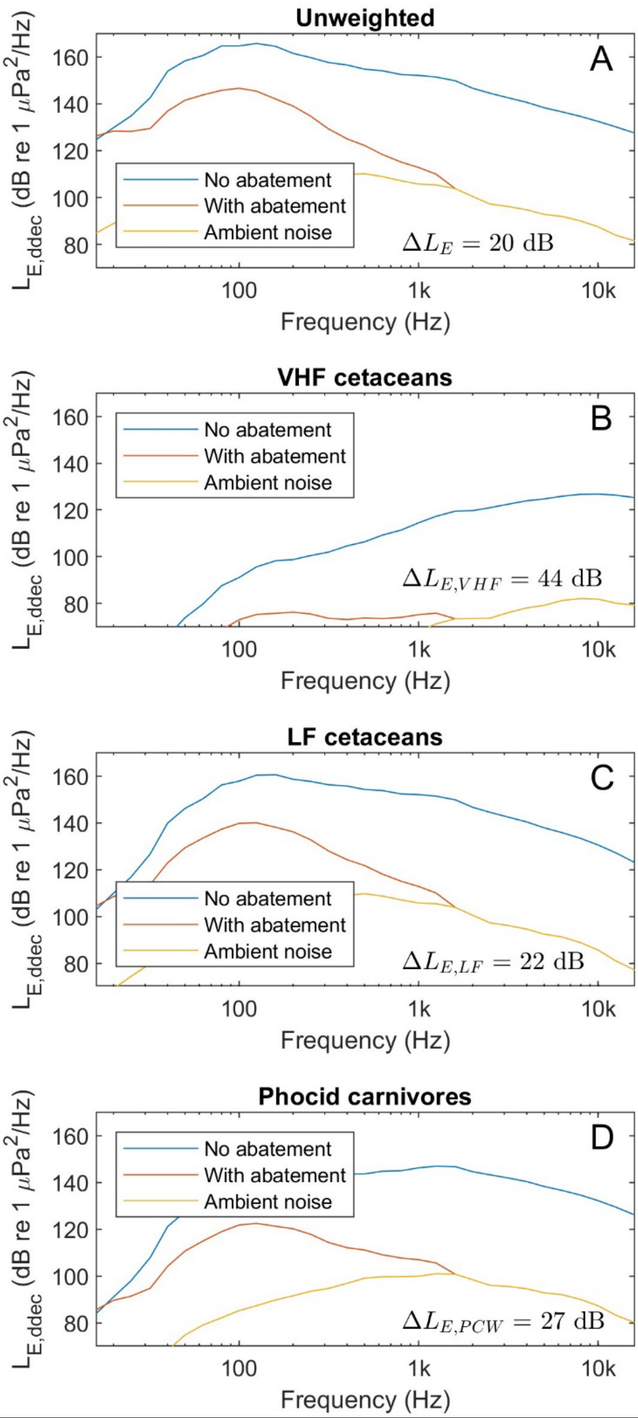

Figure 5. Effect of noise abatement on unweighted (A) and three different frequency weighted spectra (B-D). Blue curves show frequency spectra of the noise from unabated pile driving recorded 750 m from the monopile, red curves show spectra after introduction of a noise abatement system. Yellow curves show the ambient noise. Above 1.6 kHz the pile driving noise was below ambient and thus unmeasurable. For each set of curves, the difference in the total energy of the unabated and abated spectrum is shown as the $L_{abatement}$ value, calculated from Equation 3. Data replotted from Bellmann et al. (2020), Figure 33.

Neither the German noise mitigation concept, nor the Danish guidelines, specify how variation in the vertical plane – depth – should be handled. This typically leads to a worst-case assumption, where the required attenuation is calculated on the basis of the maximum sound pressure level along the depth axis. In areas such as the North Sea, where the water column typically is fully mixed, the sound speed profile is typically close to iso-velocity and there is little variation in sound pressure level with depth. In hydrographically more complex areas, such as the Baltic Sea, including Western Baltic and Kattegat, the sound speed profile varies considerably over the year. Figure 6 shows the effect of the differences in sound speed profiles on the propagation along a single radial line from the pile driving location in the Baltic Sea. Noteworthy is the increased propagation in November, seen by the higher sound levels far from the source, and the substantial difference in vertical distribution of VHF-weighted sound levels, where the presence of a sound channel close to the bottom is evident in the results for July, but not for November (the weak indication of a sound channel is likely an artefact of the monopole source approximation).

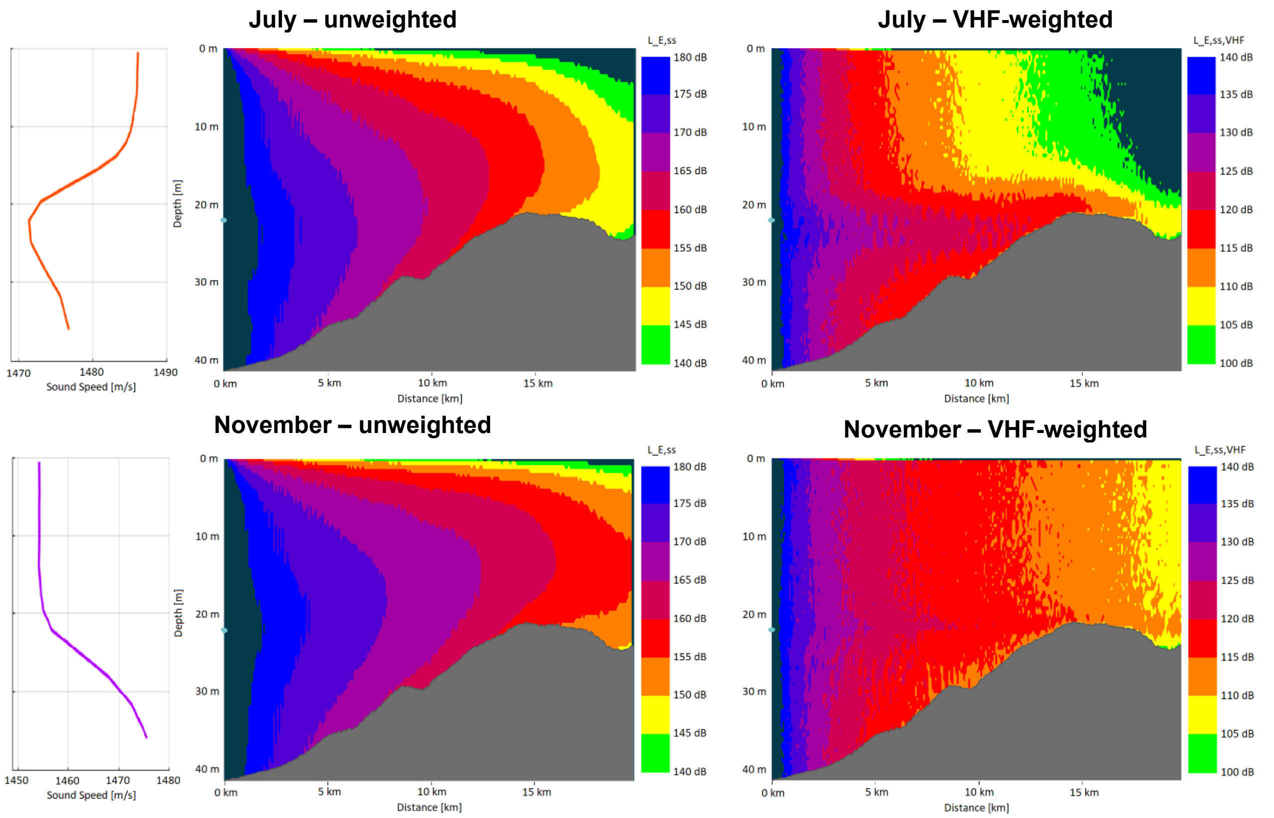

Figure 6. Vertical distribution of SEL_{SS} along a single radial (compass bearing 156°) in the Baltic Sea, modelled away from the sound source (to the left, midwater, indicated as a green dot) under two extreme hydrographical conditions. Propagation is towards and above the shallower Rønne Bank (grey shading). Left curves show the vertical sound speed profiles used in modelling. Note that colour scales for unweighted and weighted levels are different.

4 Discussion

Evaluating the requirements for noise abatement under current German and Danish legislations for the same generic pile driving event revealed substantial differences. The German noise mitigation concept is much simpler than the Danish legislation because the Danish legislation differentiates between different functional hearing groups of marine mammals and requires calculation of the cumulative received level for an animal assumed to swim away from the sound source. The noise mitigation concept is also the most restrictive legislation, as more noise abatement is required in order to comply with the German limits than with the Danish limits. In that respect, this legislation is expected to provide higher protection of the marine mammals than the Danish guidelines. As the noise mitigation concept is also the oldest and does not incorporate the newest knowledge, unlike the Danish legislation, there is, however, a risk of overregulation by the German guidelines, in particular for harbour porpoises. This was seen both in the North Sea and the Baltic Sea scenarios, where substantially higher abatement was required to comply with the noise mitigation concept, compared to the Danish guidelines (Table 1). In fact, the required abatement to comply with the noise mitigation concept was 5-8 dB more than what is currently possible to achieve with best available abatement technology (figure 5), whereas the required abatement to comply with the Danish guidelines (10 – 12 dB) was well within what is currently achievable with best available technology. The large difference between the two regulations comes about because the noise mitigation concept is based on broadband levels, whereas the Danish guidelines operate on frequency weighted levels. The broadband levels are completely dominated by the low-frequency noise where porpoises have very poor hearing. Thus, 99.9% of the energy in the unabated pile driving pulse in figure 3 is below 5 kHz, yet noise in this frequency range has little impact on the hearing of porpoises, seen from the VHF-weighting curve in figure 2 and the VHF-weighted spectra in figure 5B. Combined with the much higher efficiency of noise abatement systems at higher frequencies, the noise mitigation concept requires substantial and expensive noise abatement to attenuate the noise below a few kHz, which has almost no effect on the porpoises. Luckily, the available noise abatement systems are extremely effective in attenuating the higher frequencies of the noise, which means that a very high level of protection is achieved in the end. It is important to understand that this is not a consequence of the regulation itself, but rather a byproduct of the way sound abatement systems currently are implemented and work. A high protection of porpoises is achieved not because unweighted levels below the 160 dB re $1\mu Pa^2s$ are safe for porpoises, but because an abatement system designed to remove low frequency noise to comply with the 160 dB re $1\mu Pa^2s$ limit in most cases will be even more effective at attenuating the higher frequencies and thereby provide the protection of porpoise hearing.

Table 1. Comparison of key elements of regulatory frameworks for pile driving noise in Germany and Denmark.

	German noise mitigation concept	Danish guidelines
Source	German Federal Ministry for the Environment and Nuclear Safety (2013)	Danish Energy Agency (2023)
Threshold	160 dB re 1 μPa²s 750 m from monopile	$L_{E,cum}$ for entire piling for fleeing animal < $L_{E,PTS}$ at 200 m distance from monopile.
Scientific basis	Southall et al. (2007) Lucke et al. (2009)	Finneran (2015) Southall et al. (2019)
Documentation of compliance	$L_{E,95}$ <= 160 dB re 1 μPa²s documented by measurements at 750 m	Transmission loss model verified through measurements at different distances from piling
Includes repeated pulses	No	Yes
Includes frequency weighting	No	Yes
Handling of depth variation	Maximum over depth	Maximum over depth
Regulation of ADDs	No	Yes
Protected groups		
Porpoises	Yes	Yes, if present
Dolphins	Indirectly	Yes, if present
Baleen whales	Indirectly	Yes, if present
Seals	Indirectly	Yes, if present
Main advantage	Simple to document compliance	Targeted at specific species
Main drawback	Underestimates the effectiveness of noise abatement, except for baleen whales	Complex to estimate required abatement, and document compliance

A different, but equally important issue with the German noise mitigation concept is that it is based almost exclusively on the results of a single experiment (Lucke *et al.*, 2009). Compared to later experiments where TTS was induced in captive porpoises by pile driving noise (Kastelein *et al.*, 2015; Kastelein *et al.*, 2016) and airgun noise (Kastelein *et al.*, 2017; Kastelein *et al.*, 2020), the threshold of Lucke *et al.* (2009) stands out as significantly lower than the others, indicating higher susceptibility to hearing loss than later experiments. Recent reanalysis of the original sound recordings, however, showed that the airgun pulses used by Lucke *et al.* (2009) contained significantly more energy at higher frequencies than typical for pile driving and airgun noise (Lucke *et al.*, 2020; Tougaard *et al.*, 2022), which explains why this threshold is so much lower than the others. If auditory frequency weighting with the VHF-function of Southall *et al.* (2019) is performed on the pile driving noise, TTS-onset thresholds of all experiments with airguns and pile driving noise on porpoises, including Lucke *et al.* (2009), cluster well around the 140 dB re 1 μPa²s VHF-weighted TTS onset threshold proposed by Southall *et al.* (2019). See Tougaard *et al.* (2022) for additional details. The insight that the noise used by Lucke *et al.* (2009) is not representative of pile driving noise in general has some significant implications for the interpretation of impact ranges. If we consider the modelled scenario in the Baltic sea for November, the unweighted TTS onset threshold for a single pulse of 164 dB re 1μPa²s from Lucke *et al.* (2009) is reached at a distance of about 17 km from the pile driving site (Figure 6, lower panel, left), indicating a very high risk of impact on hearing by an unmitigated pile driving. If we instead consider the VHF-weighted TTS onset threshold of 140 dB for a single pulse from Southall *et al.* (2019) and Tougaard *et al.* (2022), this weighted level is reached only within about 1 km of the piling site (Figure 6 lower panel, right), indicating a much smaller risk of impact on porpoises, for the exact same sound source and evaluating a single pulse, in line with the logic behind the noise mitigation concept. This difference, together with the substantial empirical support for the 140 dB re 1µPa²s VHF-weighted TTS-onset threshold (Tougaard *et al.*, 2022), indicates a substantial overestimation of impact on porpoises by the noise mitigation concept. The consequence is a substantial overregulation: much more noise abatement is asked for than what is actually required to achieve the management goal (avoid TTS from exposure to single pulses beyond 750 m from the monopile).

Both the German and Danish frameworks do not consider depth in any detail. Figure 6 illustrates how the sound levels can vary substantially with depth. The vertical profiles of the VHF-weighted levels in July and November are very different, yet the estimates of the required attenuation in the two scenarios are only 1 dB apart. The explanation for this is that in both cases the cumulative exposure is calculated from maximum values along the depth axis. In July, the noise levels in the sound channel are comparable to the levels in November, but outside the sound channel, levels are much lower. This contrasts with the situation in November, where the sound levels are almost identical along the depth axis. This has important implications for the accuracy of the cumulative sound exposure estimate. In the scenario from November, the depth at which a porpoise swims would not affect the risk of impact very much, as the cumulative sum would be approximately the same. In July, however, the cumulative exposure estimate is an extreme worst-case scenario, where the animal is assumed to swim all the time within the sound channel. An animal that remains in the upper third of the water column while fleeing from the noise would experience much lower received levels and hence accumulate a much smaller exposure over the duration of the pile driving. Better knowledge about the behaviour of porpoises fleeing from the pile driving noise is needed before more realistic assumptions regarding actual exposure can be made.

Impact on dolphins and seals appears to be of lesser concern, as the required mitigation measures to protect porpoises provide more than sufficient abatement to also protect these two groups. They are therefore automatically covered once noise impacts to porpoises are accounted for. This is not the case for minke whales in the North Sea, however, which presents a separate issue of concern. The German noise mitigation concept is specifically developed for porpoises and does not deal with baleen whales as does the Danish guidelines. The Danish guidelines adopts the LF-weighted PTS onset threshold for baleen whales from Southall *et al.* (2019), which in the North Sea scenario leads to a substantial requirement for abatement (Table 1). Worse than that, this abatement is required at low frequencies, due to the weighting function of LF-cetaceans (figure 2). As noted above, it is technically more challenging and expensive to attenuate the low frequencies than the high frequency attenuation required for porpoises. This is concerning, because obtaining 24 dB of attenuation in the LF-cetacean band is about what can be achieved today with the best available noise abatement systems (Bellmann *et al.*, 2020). At the same time, it should be kept in mind that both the LF-weighting function and the PTS onset thresholds for LF-cetaceans (both from Southall *et al.*, 2019) are guesstimates not rooted in any direct empirical evidence from baleen whales. The truth is that we do not know how accurately we can estimate the risk of hearing impairment on minke whales, and we cannot count on them being covered by the protection of porpoises, as we can for dolphins and seals.

In conclusion, the two legislative frameworks compared are very different and led to very different conclusions regarding the required mitigation measures for marine mammals, when applied to the same pile driving scenarios. These large differences means that a regional harmonization across European countries is not a simple matter of merging frameworks. Consistency in protection of marine mammals against injury from exposure to excessive noise from pile driving (and other impulsive noise) probably requires development of a new framework, drawing from the experience with the existing German, Danish and other frameworks. Such a framework needs to have clearly articulated management objectives, be based on current empirical evidence, and include mechanisms for revisions, as new empirical evidence becomes available. It must also be acknowledged that such revisions can lead not only to a tightening of regulation, but also, if the empirical evidence supports it, lead to relaxation of regulation.

Abbreviations and symbols

α	Sound absorption coefficient
$\Delta L_{E,SS}$	Required attenuation by noise abatement
HF	High frequency
κ	Slope of geometric spreading loss
L_E	Sound exposure level
$L_{E,SS}$	Sound exposure level, single pulse (shot)
$L_{E,cum}$	Sound exposure level, cumulated over multiple pulses
$L_{E,PTS}$	PTS onset threshold
LF	Low frequency
L_{peak}	Peak sound pressure level
L_R	Received level
L_S	Source level
p	Sound pressure
PCW	Phocid carnivores in water
PTS	Permanent Threshold Shift
r	Distance from source
r_{start}	Distance between source and animal at start of pile driving
t	Time
T	Pulse duration
TTS	Temporary Threshold Shift
v	Fleeing speed of animal
VHF	Very high frequency

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Declaration of interests

The authors declare that they have no conflicts of interests.

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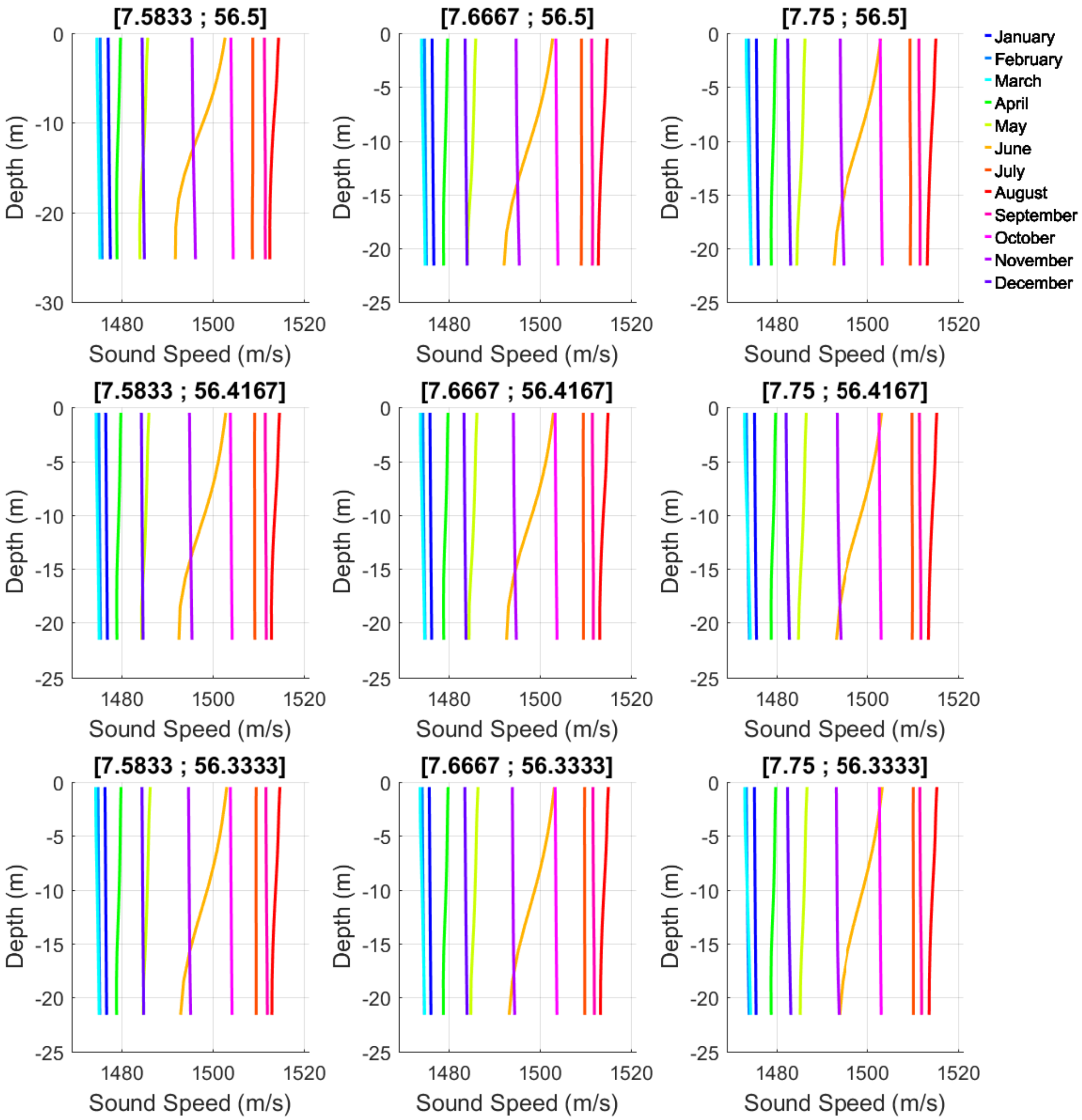
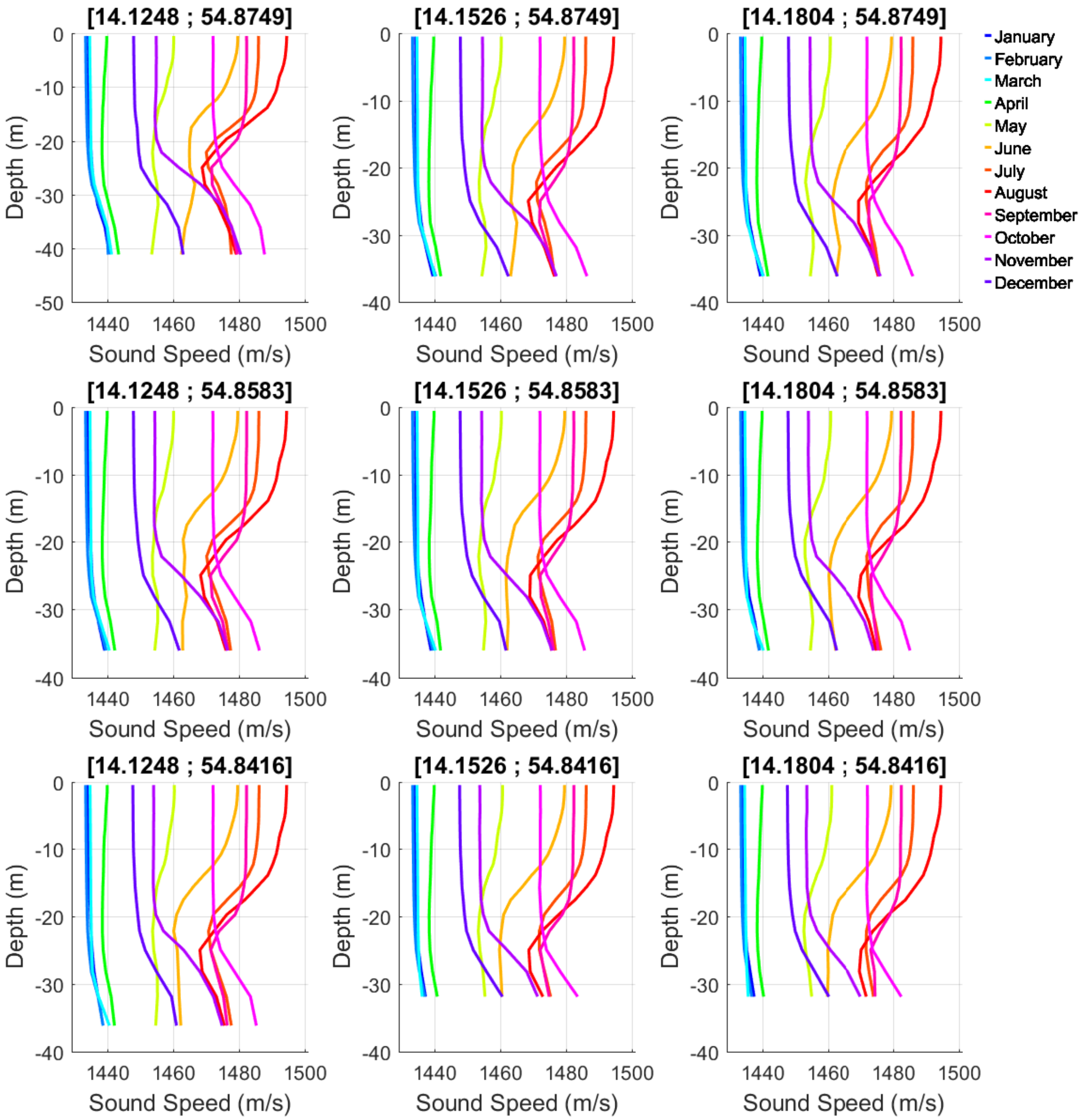
Supplementary material



Monthly vertical sound speed profiles for nine positions in the North Sea in the area surrounding modelling site 1. Positions are indicated above each plot in decimal degrees (eastern longitude, northern latitude, WGS84). Source: Copernicus, M. S. (2023). "Global Ocean Physics Analysis and Forecast model," (https://doi.org/10.48670/moi-00016).



Monthly vertical sound speed profiles for nine positions in the Baltic Sea in the area surrounding modelling site 2. Positions are indicated above each plot in decimal degrees (eastern longitude, northern latitude, WGS84). Source: Copernicus, M. S. (2023). "Global Ocean Physics Analysis and Forecast model," (https://doi.org/10.48670/moi-00016).