Appendix 2

Model-calculations results

Numerical modelling of noise propagation from pile driving in the Baltica OWF Area

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- Thomsen Frank, Stöber Uwe, Yalçin Gülce, Sehested Hansen Ian, Environmental Impact Assessment of the Baltica 2 and 3 Offshore Wind Farms. Numerical Modelling of Noise Propagation from Pile Driving, Technical report, Denmark 2017.
- Thomsen Frank, Stöber Uwe, Yalçin Gülce, Sehested Hansen Ian, Environmental Impact Assessment of the Baltica 2 and 3 Offshore Wind Farms. Numerical Modelling of Noise Propagation from Pile Driving, Appendices, Technical report, Denmark 2017.
- Thomsen Frank, Stöber Uwe, Yalçin Gülce, Kamp Sørensen Mikael, Cumulative Environmental Impact Assessment of the Baltica Offshore Wind Farm. Numerical modelling of noise propagation resulting from pile driving at several sites, Technical report, Denmark 2017.

Contents

Abbreviations and definitions 5
1 Non-technical summary 6
2 Introduction 8
3 Methods 9
3.1 Modelled area and environmental factors 9
3.1.1 Sound velocity profile 11
3.1.2 pH 13
3.1.3 Seabed profile 14
3.2 Noise modelling 14
3.2.1 Sound source information 16
3.2.2 Sound propagation modelling 19
3.2.3 Sound attenuation in water 21
3.2.4 Noise mitigation system 21
3.2.5 Cumulative sound exposure level 22
3.3 High frequencies transmission losses 22
3.4 Threshold values 24
4 Modelling of noise propagation as a result of a single location piling 25
4.1 Sound levels 25
4.1.1 Weighing 26
4.2 Results of the numerical modelling of propagation of sound generated in the Baltica 2 Area 27
4.2.1 Sound propagation model in the case of a single strike of a pile driver 27
4.2.2 Impact range 33
4.3 Results of the numerical modelling of the propagation of sound generated in the Baltica 3 Area 38
4.3.1 Sound propagation model in the case of a single strike of a pile driver 38
4.3.2 Impact range 44
5 Modelling of noise propagation as a result of single location piling 50
5.1 Methods 51
5.1.1 Superimposition of the noise from sources located near each other (<1 km) 51
5.1.2 Superimposition of the noise from sources at a medium distance from each other (20 km) 51

5.1.3 Superimposition of the noise from sources located far each other (<1 km) 52
5.2 Results 52
5.2.1 Grey and harbour seals 52
5.2.2 Porpoises 57
5.2.3 Ichthyofauna 61
5.3 Simulation of the noise accumulation with the noise generated by other OWFs 69
6 Summary 73
6.1 Noise propagation from pile driving in a single location 73
6.1.1 The impact zone of the pile driving in the Baltica 2 Area 73
6.1.2 The impact zone of the pile driving in the Baltica 3 Area 74
6.2 Noise propagation from pile driving works performed in several locations 74
7 References 76
8 List of tables 78
9 List of figures 79

Abbreviations and definitions

BBC	Big bubble curtain used to mitigate underwater noise emissions during offshore pile driving
BŚII	The Offshore Wind Farm “Polenergia Bałtyk II” (formerly known as “Bałtyk Środkowy II”)
BŚIII	The Offshore Wind Farm “Polenergia Bałtyk III” (formerly known as “Bałtyk Środkowy III”)
dB	Decibel, logarithmic unit used to express the intensity of a sound wave/pressure
DBBC	Double big bubble curtain used to mitigate underwater noise emissions during offshore pile driving
EIA	Environmental impact assessment
HF	Functional hearing group – cetaceans – after NMFS 2016
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
OWF	Offshore Wind Farm
PSU	Practical Salinity Unit
PTS	Permanent threshold shift
PW	Functional hearing group – pinnipeds – after NMFS 2016
RAM	Range-dependent acoustic model
SEL	Sound exposure level
SEL_{cum}	Cumulative sound exposure; the sum of multiple sound exposure levels, e.g. multiple hammer strikes
SL	Sound level
SPL	Sound pressure level
TL	Acoustic waves attenuation, transmission loss
TTS	Temporary threshold shift
UAS	Underwater acoustic simulator
WOA	World Ocean Atlas
WOD	World Ocean Database

1 Non-technical summary

Sound may be generated during all stages related to constructing, operating and decommissioning of an offshore wind farm. The greatest impacts are associated with underwater noise, emitted during the construction of offshore wind farms. This is due to generating high level sound created during pile driving into the sea-floor (piling). Marine biota such as fish or marine mammals are susceptible to sounds, therefore the sound that accompanying the activities linked to the construction of wind farms may affect them over long distances through:

- behavioural changes, including avoidance;
- temporary hearing loss;
- long-term of permanent hearing loss.

Various applied methods of construction wind farms generate into the marine environment sounds with various characteristics. The local topography of the seabed and other environmental factors make sound propagation in the water environment specific for a specific area. Additionally, each wind farm area is populated or used by various organisms, which have different hearing characteristics. Therefore, the impact of the underwater noise generated during the construction of a wind farm must be assessed step by step, taking into consideration the unique characteristics of a specific project.

In this technical report the acoustic noise emission accompanying piling in the Baltica OWF Area has been examined.

Noise propagation modelling has been carried out for the piling locations near the centre of the Baltica 2 and Baltica 3 Area. The Baltica OWF Area is relatively small in comparison to the range of the sound generated during piling. Sound propagates over relatively large distances from its source. Therefore, the differences in sound attenuation for various locations do not cause significant differences in the length of anticipated impact zones. For the purpose of the modelling a region with a diameter of at least 150 km in all directions from the sound source was designated by setting 72 azimuthal paths 150 km long each (taking into account the barrier in the form of the coastline).

The numerical underwater noise modelling was carried out for the worst-case scenario which is piling (pile diameter – 12.5 m), after taking into account the use of the noise mitigation system and assuming – for the purposes of noise modelling – the efficiency of noise reduction typical for currently available technical measures e.g. a bubble curtain. It has been assumed that at the time of the implementation of the investment other technical measures might be available which would enable to achieve at least the same noise level as with the use of the bubble curtains.

The sound level within 1 m (the source level) has been expressed as the sound exposure level (SEL), that is the sound level averaged for 1 second (in dB re 1 $\mu Pa^2 \cdot s$). The sound levels at source have been also expressed as atmospheric pressure peak levels (in dB re 1 µPa). Values have been determined for both: single strikes of a pile driver and for sequences of strikes (so-called cumulative sound exposure level), up to a maximum number of strikes estimated as possible to achieve within 1 hour. The values used in the modelling were the following:

- atmospheric pressure peak level for a single strike (SPL_{peak}): 230.6 dB re 1 µPa);
- sound exposure level for a single strike of a pile driver (SEL): 210.6 dB re 1 $\mu Pa^2 \cdot s$;
- cumulative sound exposure level for multiple (1 hour) strikes of a pile driver – approx. 2800 strikes (SEL_{cum}): 245.1 dB re 1 $\mu Pa^2 \cdot s$.

Based on the acoustic modelling, two noise impact zones (a distance from the sound source) affecting marine mammals (grey and harbour seals and porpoises) as well as fish occurring in the Baltica 2 and Baltica 3 Areas have been assessed.

Sound levels have been estimated assuming the use of the noise mitigation system. Currently available solutions include e.g. a bubble curtain producing a circle of air bubbles around the area of driving a pile into the sea-floor which causes reflection and absorption of underwater noise, and therefore – the reduction of the noise level audible during piling. Based on the available literature, the efficiency of noise mitigation level of 13 dB has been assumed.

Sound propagation modelling has been carried out for the frequency spectrum of 20 Hz – 2.5 kHz which covers most of the acoustic energy emitted during piling. Hearing frequency range for marine organisms reaches 20 kHz and for the frequency range between 2.5 kHz and 20 kHz a conservative estimation of the transmission loss has been applied, including the sea-bed topography as well as sediment composition in the area and leading to an upper estimate of the sound intensity level. The numerical calculations have been carried out with the use of a MIKE Underwater Acoustic Simulator (UAS) developed by the DHI.

Based on the modelling carried out it was demonstrated that sound propagation to a large extent depends on the seabed topography, which results in differences in directionality of the sound propagation intensity. The impact zones have been estimated with the use of the noise mitigation system. It has been demonstrated that for a single strike the behavioural changes zone for seals is 4.5 km in the case of the source located within the Baltica 2 Area and 4.6 km within the Baltica 3 Area. The range of the TTS and PTS zones in the case of seals is smaller than 0.1 km. For porpoises the TTS impact zone reaches 1.8 km for the Baltica 2 Area and 1.9 km for the Baltica 3 Area. The average range of the PTS impact is smaller than 0.1 km. The range of the impact causing behavioural changes (avoidance) is 46 km for porpoises for the Baltica 2 Area and 42 km for the Baltica 3 Area. In regard to ichthyofauna, for fish with and without the swim bladders the TTS and PTS range was smaller than 0.1 km. The difference in range has been observed in the case of behavioural changes. In regard to fish without the swim bladders the impact range was maximum 33 km and for fish without the swim bladders it was 76 km.

The results of the impact range for multiple strikes of a pile driver, lasting around 1 hour during piling with the use of the noise mitigation system are greater than those obtained for a single strike.

Due to a possibility of a situation when in a specific area simultaneous piling in two or more sites takes place, modelling aimed at defining potential noise accumulation and its impact on marine mammals and ichthyofauna has been carried out.

Based on the assessments carried out, it has been concluded that it is the number of sources, not the distance between them that is significant to the magnitude of the impact. The modelling results indicate that simultaneous piling in two sites has negligible significance for porpoise and seals, however it possibly affects ichthyofauna. Three of four localization of simultaneous piling would entail a significant impact on ichthyofauna and porpoises, regardless of the source of the noise distribution. In the case of seals even simultaneous piling in 4 localizations generates negligible impact. Therefore, it is recommended that works in the Baltica OWF Area and other nearby OWF Areas (BŚII and BŚIII) should be arranged in such a way so that there are no more than 2 simultaneous pilings.

2 Introduction

This paper constitutes a technical report which is a support EIA Report document in regard to the noise propagation modelling and its impact on marine mammals and ichthyofauna. It contains the results of the numerical modelling of propagation of the sound spreading as a result of the noise generated by the foundation installation with the worse-case scenario of the maximum variant of the Baltica OWF after taking into account the noise mitigation system. Generated sound levels have been compared with the registered acoustic background spectrum in order to demonstrate changes within the acoustic field during the construction of the OWF.

Piling is currently the most frequently used method of the wind power stations foundation settlement on the seabed. The following types of foundations: multidimensional pile, three-pole derrick and lattice foundation require an assessment of the impact of piling on the environment. Gravity based structures do not require piling, but they require the preparation of the seabed through dredging which also causes noise and additionally churns the sediment.

In this project a large diameter pile type of foundation has been recognized as the worst-case scenario. It has been demonstrated that erecting construction of this type on the seabed goes hand in hand with the highest intensity of the sound emission. During engineering works piles are driven into the seabed with the use of the hydraulic hammer which causes high acoustic pressure – noise (Nedwell and Howell, 2004; Thomsen, 2010).

The noise created during piling is characterized by a relatively wide range covering the frequency range between 20 Hz and 20 kHz (Nedwell and Howell, 2004; Madsen et al., 2006), but most of the acoustic energy is emitted in the low frequency range below 1 kHz (Figure 1).

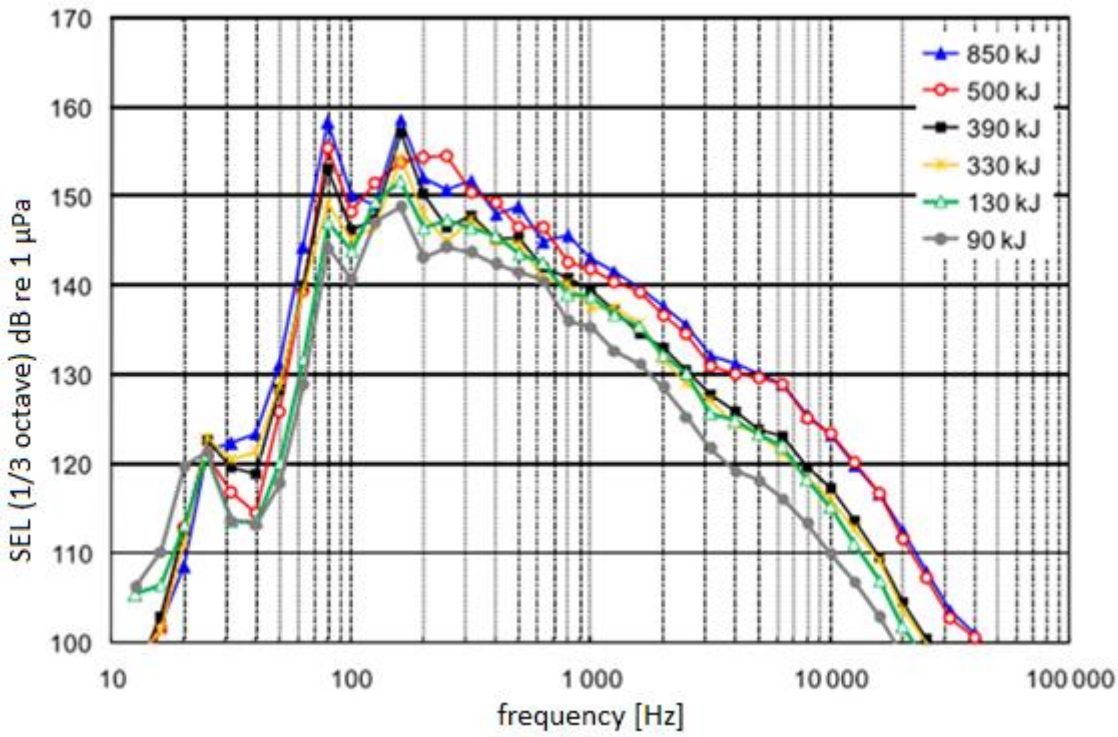

Figure 1. Spectral noise level in relation to the strike energy

Source: internal data based on Betke (2008)

In order to establish the most unfavourable scenario, four types of foundations considered for the use in construction of the Baltica OWF have been analysed as sound sources. The analysis has been carried out on the basis of the acoustic field calculations in the form of a cumulative sound exposure level (SEL_{cum}) emitted to a water column. The cumulative sound exposure level is the most suitable analytical indicator of the "acoustic dose" generated during anthropogenic activity. Basically, in order to assess the "dose" sound levels generated by single acoustic incidents (single strikes of a pile driver) are summed up. It has been established that the most unfavourable scenario with the highest potential impact on marine life in the assessed area is the variant in which a large diameter pile with a diameter of 12.5 m was used.

3 Methods

3.1 Modelled area and environmental factors

Acoustic modelling for piling has been carried out for two sites which constituted the central points of the Baltica 2 Area and the Baltica 3 Area (Figure 2).

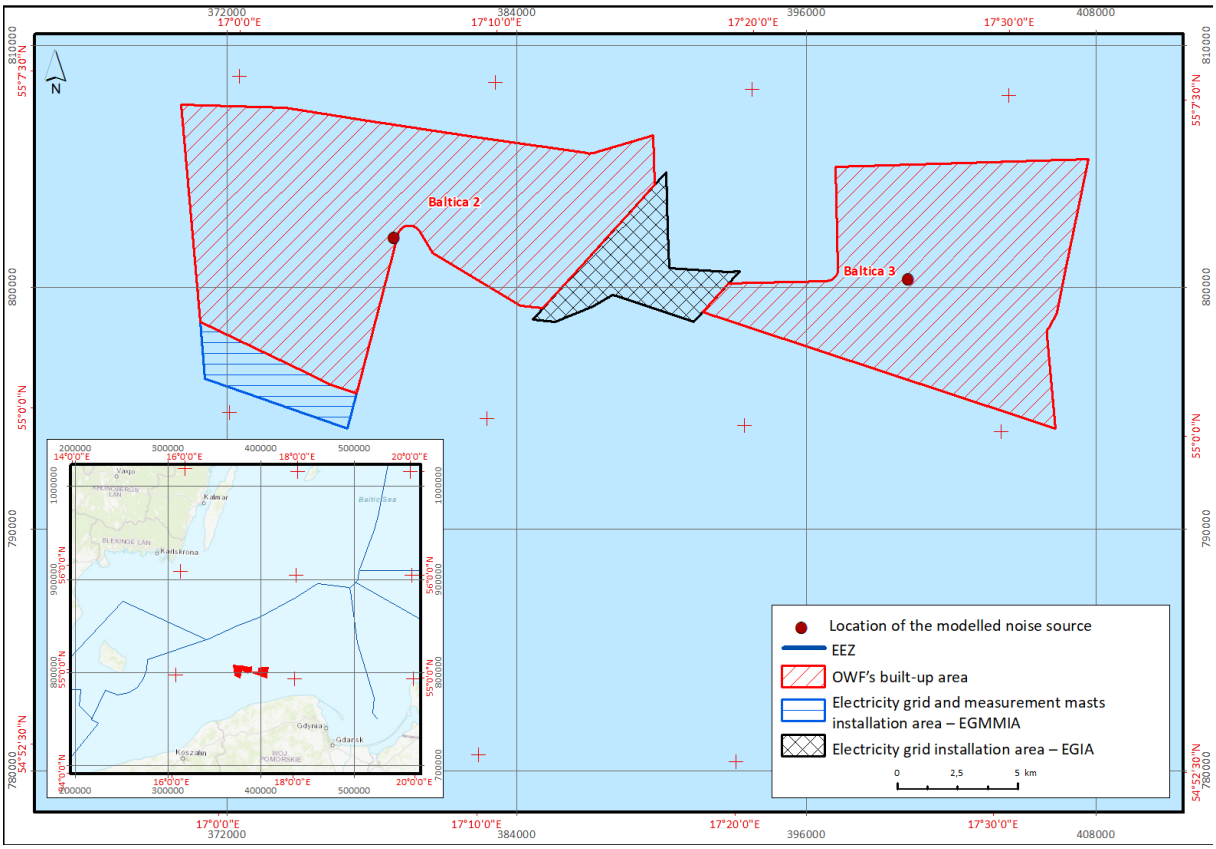

Figure 2. The sites of the Baltica 2 Area and the Baltica 3 Area along with the site of the modelled sound sources constituting the central points

Coordinates of the centre of the Baltica 2 Area: 55.0669°N 17.1034°E, coordinates of the centre of the Baltica 3 Area: 55.0561°N 17.4377°E

Source: internal data

The sites of the sound sources were chosen is such way so that they constituted the best spatial representation of all potential sound sources in the areas of the planned undertakings. Moreover, the surface area of the planned undertaking is small in relation to the acoustic field range of the

noise generated during piling, because the sound generated during piling can travel through relatively large distances from the sound source (Thomsen et al., 2006).

Therefore, the differences in sound spreading in other positions will not results in significant discrepancies in anticipated impact zones ranges. Based on the previous research and data from the literature regarding the sound propagation as a result of piling (Thomsen et al., 2006), it has been established that the area subjected to modelling should include the region within at least 150 km from the sound source in all directions (Figure 3, Figure 4). Therefore 72 azimuthal paths with the length of 150 km have been designated, each taking into account the barrier in the form of the shoreline.

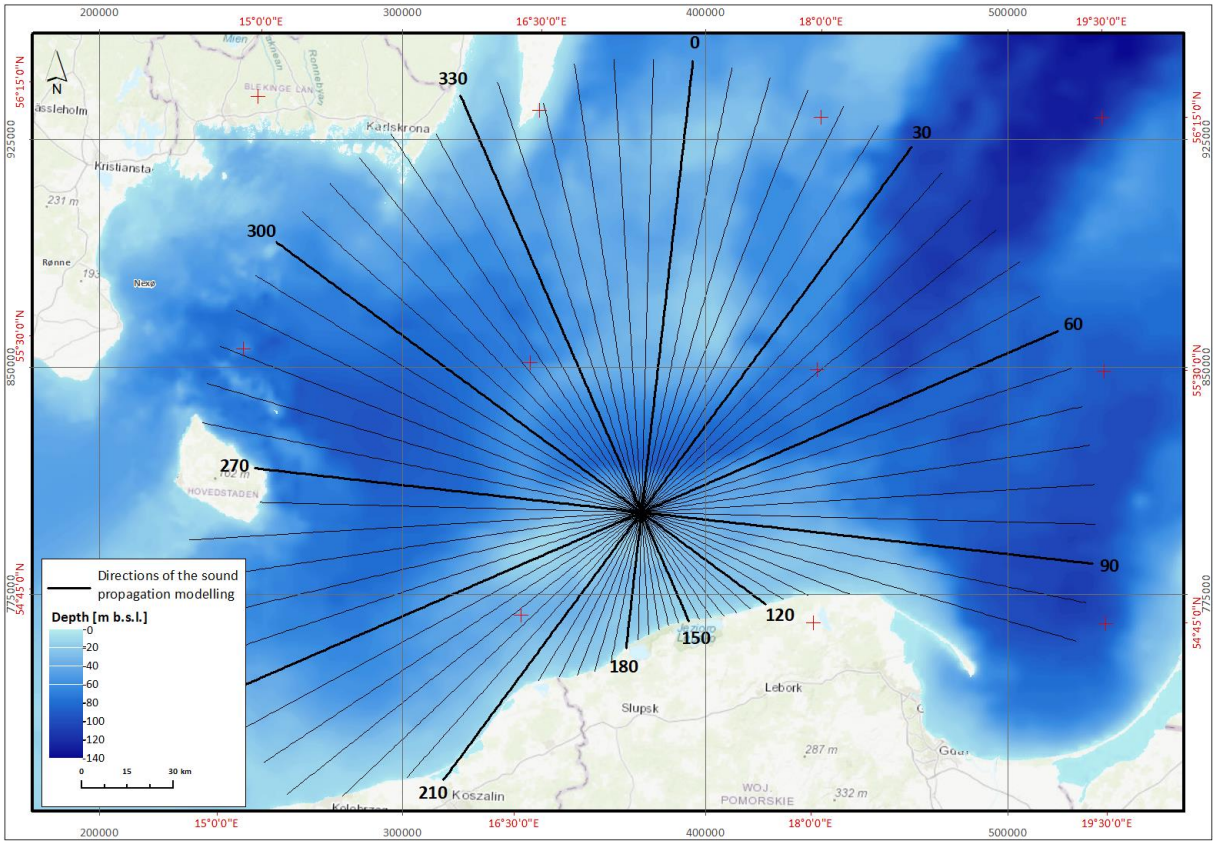

Figure 3. Directions of the sound propagation modelling in the Baltica 2 Area

Source: internal data

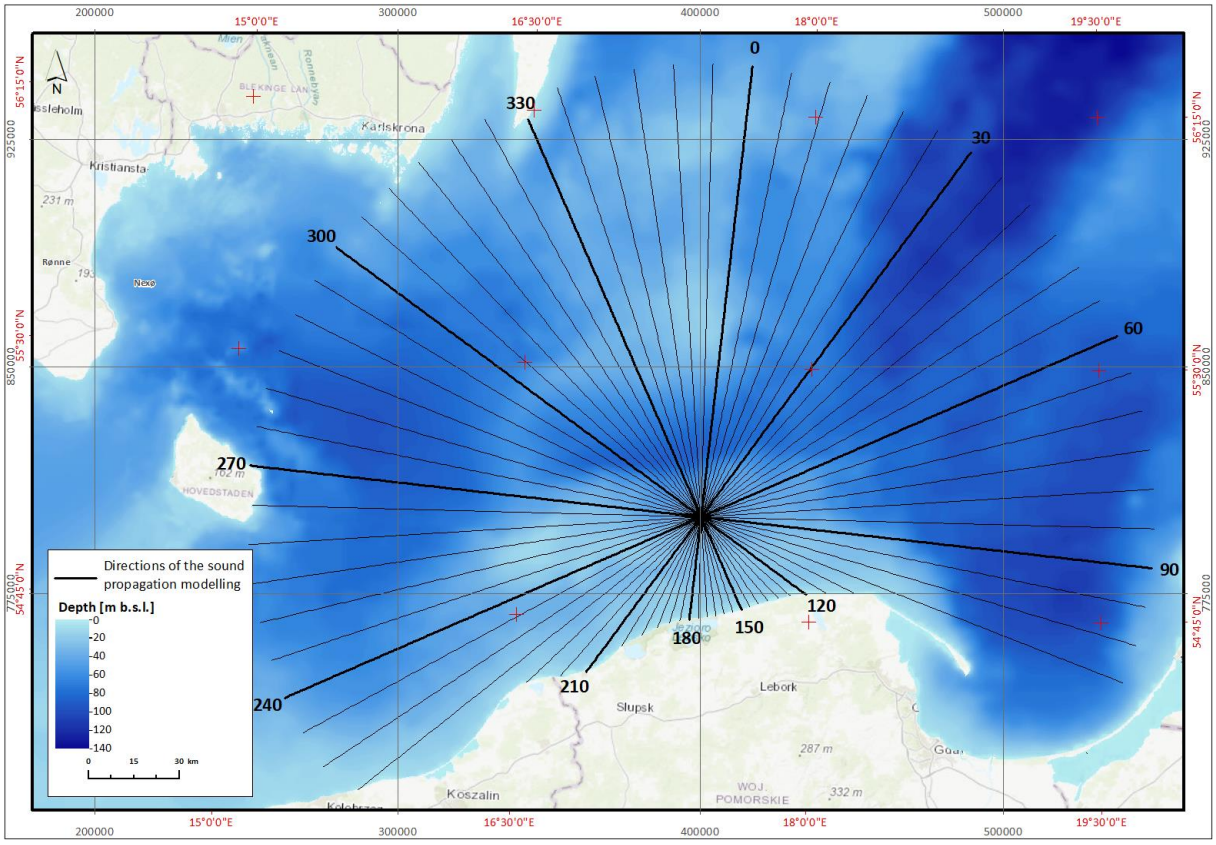

Figure 4. Directions of the sound propagation modelling in the Baltica 3 Area

Source: internal data

From the point of view of acoustics, the Baltica 2 and the Baltica 3 Areas are considered to be the areas of shallow water.

3.1.1 Sound velocity profile

Sound velocity profiles have been based on the temperature and salinity of waters obtained from the NOAA World Ocean Atlas (Locarnini at al., 2013; Zweng at al., 2013) for the area covering the modelled region and with the division into 4 seasons with the use of the equation UNESCO (UNESCO, 1983). Sound velocity profiles as well as temperatures and salinities have been presented below (Figure 5).

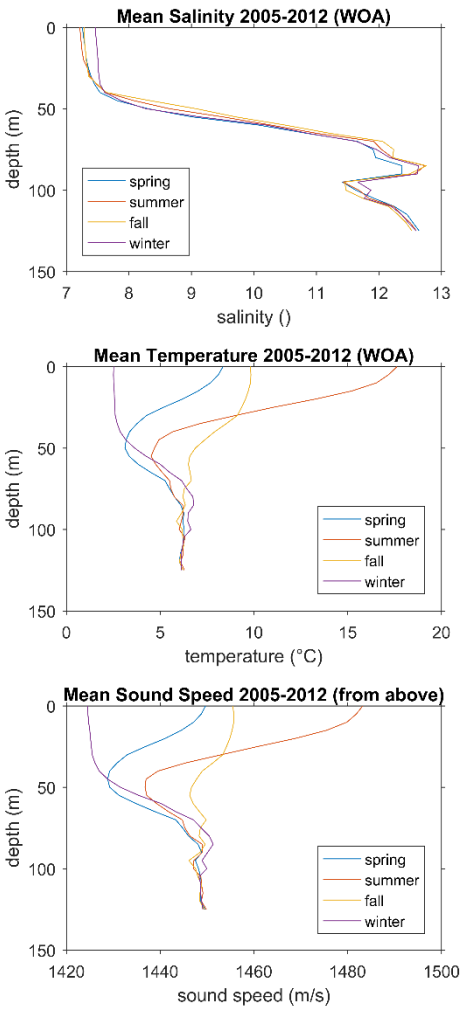

Figure 5. Seasonal changes of salinity, temperature and sound velocity

Source: internal materials based on data from the NOAA World Ocean Atlas in the years 2005–2012

Profiles for the seasons of summer and autumn show a refractive tendency towards the seabed (Urick, 1983). This phenomenon is compliant to the Snell's law stating that the acoustic wave bends (refracts) towards the area with the smaller sound velocity. The implication of this law for the sound in water consists in the fact that the sound, penetrating a water column where the density is smaller, might be trapped there. This results in the phenomenon where the sound can be transmitted to long distances with very small transmission loss.

Most of the area surrounding the site has a depth of less than 50 m. This makes the acoustic waves bend towards the seabed and the waves interactions with the seabed occur more extensively than with the water surface. The acoustic waves are partially absorbed and reflected from the seabed. This has a significant influence on the transmission loss depending on the sediments making up the seabed.

During the seasons of winter and spring the lowest sound velocity in a water column has been observed at depths of 20–40 m. Due to the acoustic waves refraction towards the areas where the sound velocity is smaller, this part of the profile constitutes a perfect acoustic channel. Therefore, a part of the energy generated by the sound source is trapped in a wave guide which enables its propagation to very large distances with small losses.

Similarly, to the seabed – the surface of water constitutes a boundary which might have a significant influence of the sound propagation. This effect is visible during a high sea state, when an upward refraction occurs. Apart from the propagation paths where partial wave energy loss occurs, resulting from sound scattering at the rough sea surface, sound waves will be attenuated in the upper layer of a water column following the presence of a large amount of air bubbles created as a result of the waves refraction. Significant absorption of noise as a result of scattering – the mechanism of loss, interference and sound wave fluctuation – from the resonant air bubbles is caused by the fact that the geometrical size of the bubbles at the resonant frequency appears much larger than in reality (Matuschek and Betke, 2009).

Apart from the increased transmission loss resulting from scattering, the sound is also attenuated as a result of refraction associated with different on a spatial scale sound velocity. Although the volume concentration of air bubbles is relatively small – it usually constitutes around 1% – it has a huge impact on sound velocity even at the small air concentration (Jensen et al., 2011). Sound attenuation resulting from the presence of air bubbles applies mainly to the acoustic propagation of the high frequency sounds. Therefore, introducing the air bubbles surrounding the sound source is a very effective mitigation method.

3.1.2 pH

In order to determine sound attenuation values in a water column, underwater noise modelling software MIKE Underwater Acoustic Simulator (UAS), apart from the salinity and temperature profiles used for reaching the sound velocity profile, additionally requires setting a pH profile. The UAS uses the empirical model developed by Francois and Garrison (1982a, 1982b) which takes into account the absorption of boric acid, magnesium sulphate and pure water.

Data regarding the pH have been obtained from the database of the NOAA World Ocean (Boyer et al. 2013) through the search system WODselect. The pH profile (Figure 6) has been generated from the set of 238 profiles recorded in the region of the model in the years 2005–2015. The seasonal variability range is small in comparison to the whole profile range. The profile is extrapolated up to 130 m which corresponds to the maximum existing depth in the modelled area, but the values below 7.5 were replaced with the value of 7.5 so that they matched with the empirical model of Francois and Garrison (1982a, 1982b).

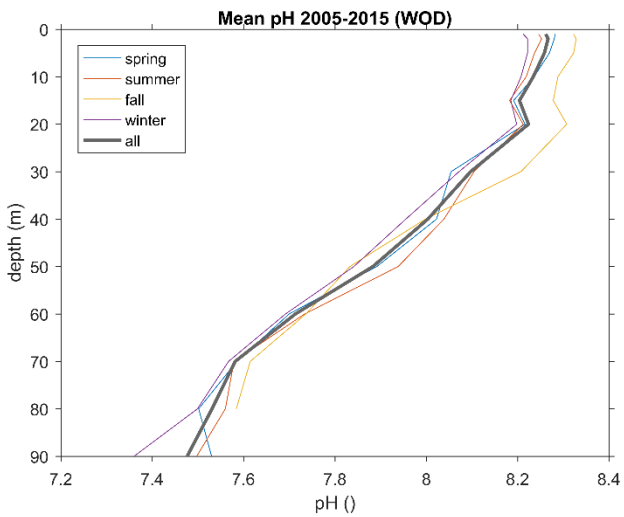

Figure 6. Seasonal changes within the pH range

Source: internal materials based on the data from the NOAA World Ocean Database in the years 2005-2015

3.1.3 Seabed profile

The seabed profile has been prepared on the basis of the publication of Rudowski et al. (2013) and on the basis of general information regarding the surveyed area. The data regarding the sediment layers constituting the seabed are presented below (Table 1).

Table 1. Geoacoustic parameters of the seabed used in the acoustic modelling

Seabed layer [m]	Type of sediment	Geoacoustic properties
0-2	Sand	C_p = 1650 m/s α = 0.8 dB/λ ρ = 1.90 g/cm^3
2–22	Post-glacial sediments, coarse grained sediments	C_p = 1950 m/s α = 0.4 dB/λ ρ = 2.10 g/cm^3
>22	Bedrock	C_p = 2400 m/s α = 0.1 dB/λ ρ = 2.20 g/cm^3

C_p – compressed wave velocity
α – compressive attenuation
ρ – density
Source: internal data

Under assumed geoacoustic conditions of the seabed, a rapid sound absorption is expected due to the interaction with the seabed.

3.2 Noise modelling

The sound created as a result of piling is instantaneous and of a discontinuous (impulsive) nature. Acoustic energy is generated as a result of the impact of the hammer. A wave of compressing stress appears and moves down the pile and the surrounding medium – first the air, further down the pile – the water, down to the seabed. The acoustic energy travels to a water column via various paths:

- from the top part of the pile where the hammer strikes through the air to water;
- from the top part of the pile downwards, thus radiating to the air, and as moving downwards – from the air to water;
- from the top part of the pile downwards, radiating directly to the water at the section of the pile which is under the surface of water;
- down the pile, radiating towards the seabed and then upwards through the seabed. As the acoustic waves propagation takes place, the sound will be "leaking" towards a water column, where it will be a value added to the sound coming to the receiver. This way the sound radiates back to the water column. Because the sound velocity is generally higher in homogeneous sediments than in water, the waves usually reach the recipient before the wave propagating in water;
- In the lower part of the pile the impulse power will make the pile drive into the sea-floor. The energy is transmitted from the hammer to the pile not only through the structural waves radiating down the pile, generating the transverse waves in the seabed, but also through the medium pressure on the seabed (Nedwell and Howell, 2004).

The sound in water is subject to reflection and refraction. At a small distance from the pile the acoustic energy propagates via various routes in various phases and with delays which causes appearance of enhancing and attenuating interferences. Further away from the pile predominates the energy coming from water and the seabed. In the flexible seabed the sound travels in the form of a compressed pressure wave and a transverse wave S. The sounds can propagate through some types of the seabed very quickly and with a very slight attenuation. The waves S are the most evident in stony sediments. Reinhall and Dahl (2011) published a detailed research paper regarding the noise generation and propagation in relation to piling, focusing mainly on the near field.

The sound level in a water column at some distance from the pile depends on:

- the size, shape, length and material the pile is made of;
- the size and energy of the hammer;
- the type and thickness of the sediment;
- the depth and type of the seabed;
- the depth of water (the shallow water channel in this report);
- the salinity and temperature of water;
- attenuation due to viscosity, pressure, salinity and acidity.

The temperature and salinity changes in coastal waters influence the sound refraction in a water column. These properties are the most significant for the acoustic energy transmission, particularly in shallow waters where irregular sea-floor and statistically varied water surface occurs.

In general, for the shallow coastal water environment – the lower sound frequency, the further the sound is propagated. On the other hand, high frequency sounds are more absorbed, particularly when the depth decreases as the sound source recedes. In such conditions greater interaction of the sound with the seabed takes place and consequently – the sound is absorbed faster than in the areas of greater depth. In shallow waters geometric spreading of the sound e.g. cylindrical or spherical transmission loss might also be significant.

The acoustic wave propagation towards shallow waters has been presented below, thus depicting the increased interaction of the wave with the seabed and the surface of water (Figure 7).

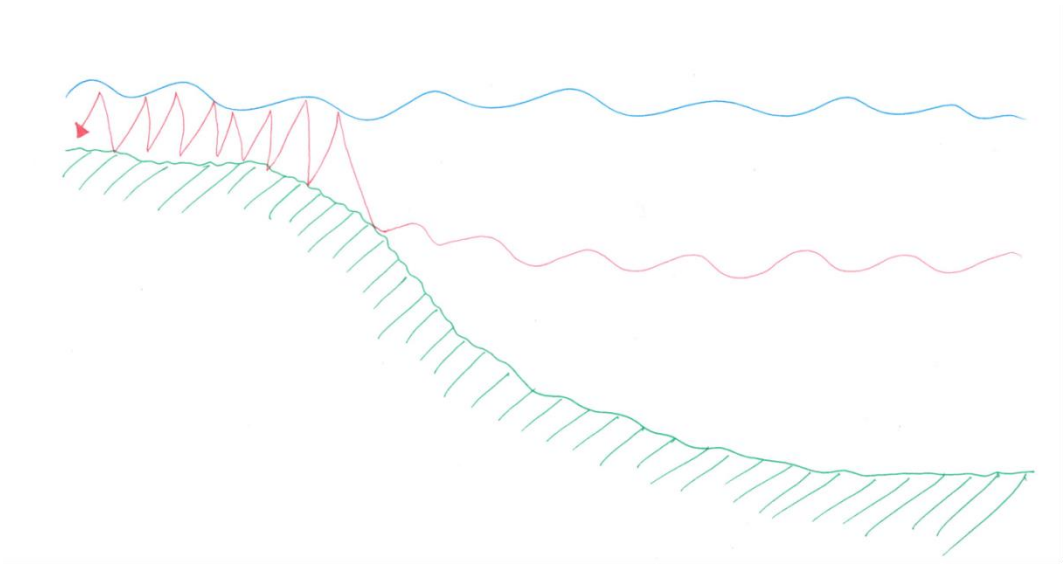

Figure 7. A diagram of propagating acoustic wave from the deep to the shallow waters and the increase of interaction with the seabed and the surface of water

Red line – acoustic wave
Blue line – surface of water
Green line – seabed
Source: internal data

3.2.1 Sound source information

In order to establish the most unfavourable scenario, four types of foundations considered for the use in construction of the Baltica OWF have been analysed as sound sources (Table 2). Floating foundations which require anchoring have been excluded in these reflections. In the case of the floating foundation anchoring, piling might be necessary, but its impact will be much smaller than any other foundation laying. The analysis has been carried out on the basis of the acoustic field calculations in the form of a cumulative sound exposure level (SEL_{cum}) emitted to a water column. The cumulative sound exposure level is the most suitable analytical indicator of the "acoustic dose" generated during anthropogenic activity. Basically, in order to assess the "dose", sound levels generated by single acoustic incidents (single strikes of a pile driver) are summed up.

It has been established that the most unfavourable scenario with the highest potential impact on marine biota in the explored area is the variant in which a large diameter pile with a diameter of 12.5 m has been used. Therefore, the impact assessment will be further based on this more unfavourable scenario. It must be noted that the most unfavourable scenario includes the sound propagation conditions for the Baltic Sea typical for the spring season. It has been assumed that a single-point source of sound is placed at the depth of 20 m (approximately the half of a water column) and is located in the central points of the Baltica 2 and Baltica 3 Areas (Figure 2).

Table 2. Underwater sound emissions from pile driving

Parameter	**The type of foundation**				
	Large-diameter pile	**Large-diameter pile**	**Tripod**	**Jacket**	**Jacket**
The diameter of the pile [m]	10	**12.5**	2.5	1.8	3

Parameter	The type of foundation				
	Large-diameter pile	Large-diameter pile	Tripod	Jacket	Jacket
The number of pile driver strikes per pile	14,000	**16,800**	8400	8400	8400
The number of pile driver strikes per hour	2800	**2800**	2800	2800	2800
The number of pile driver strikes per foundation	14,000	**16,800**	25200	33,600	33,600
Pile hammer energy [kJ]	3000	**3000**	2300	2300	2300
SEL (dB re 1 µPa^{2}s)	220	**223.6**	210	206	210
SPL_{peak} (dB re 1µPa)	240	**243.6**	230	228	230
SEL_{cum} for a 1 h period (dB re 1 µPa^{2}s)	254.4	**258.1**	244.4	240.4	251

The variants with possibly the strongest impact has been marked in bold
Source: internal data based on Betke (2008)

The above table is a comparison of the underwater sound emission during piling in relation to the construction of an offshore wind farm, based on a single strike and multiple strikes of a pile driver. The sound levels for the pile with a diameter under 5 m have been read from the curve proposed by Betke (2008), and then for the pile with a diameter of over 5 m the extrapolation of this curve has been carried out. The SPL stands for the sound pressure level, and the SEL – the sound exposure level, which is a measure of the acoustic energy of a single strike or multiple strikes in a specific period. Both values have been given in reference to the pressure value equal 1 µPa.

3.2.1.1 Sound source spectrum

The source frequency spectrum has been determined on the basis of a distinctive sound coming from a single strike of a pile driver recorded within 400 m from a pile with a diameter of 1.5 m at the depth of 25 m (Thomsen et al., 2006). This spectrum covers the frequency range between 20 Hz to 20 kHz, but most of the energy is located in thirds with central frequencies 100 Hz, 315 Hz and 1 kHz. Due to the fact that over 97% of a total energy within a full range from 20 Hz to 20 kHz is contained within the range between 20 Hz and 2.5 kHz, the modelling has been carried out for this band. For the remaining part of the band a conservative assumption that the transmission loss is not greater than the transmission loss for 2.5 kHz has been accepted. As shown in the section 3.2.3 the sound absorption in water increased with the frequency increase (Figure 9) and this is an upper estimate of a sound exposure level.

The analysis has been carried out in the frequency bands with the width of 1/3 of an octave (thirds), because it is known that in biological hearing systems the sound is integrated in an array of band filters – the frequency bands called critical bands. The width of the band equals approximately a 1/3–1/12 part of an octave, whereby the Q value (the value corresponding to the frequency width divided by the central frequency) is a constant for most species of marine animals. To simplify – according also to the results of other surveys (e.g. Madsen et al., 2006), the ambient noise levels are calculated in the frequency 1/3 octave-bands (Thomsen et al., 2006).

A weight function suggested by the NOAA which is applied to marine mammals using for echolocation high frequency range – HF (NMFS, 2016) – has even more influence on the shape of the frequency spectrum of the sound source: the greatest amount of the spectral energy is localised within the frequency range between 3.15 and 16 kHz (Figure 8, orange line).

After the application of the weight function suggested by the NOAA for pinnipeds – PW (NMFS, 2016) – the most energy-filled band was a third with the central frequency of 1 kHz (Figure 8, yellow line), a relative contribution of the high frequency components increases as a result of the reduction of the low frequencies influence. The frequency range assumed in the modelling covers around 80% of the total energy contained within the full range from 20 Hz to 20 kHz which corresponds to the difference of 1 dB between the noise expose level in a wide and restricted frequency bands.

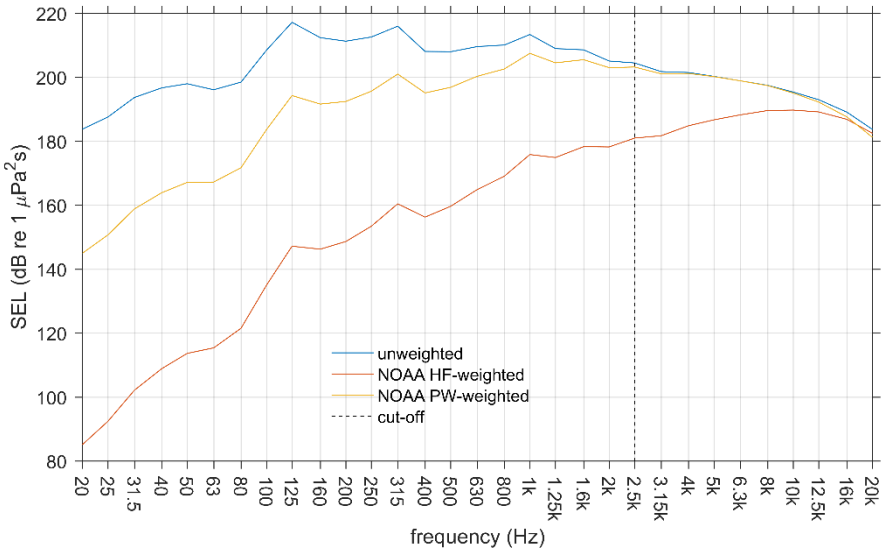

Figure 8. The model frequency spectra of the sound generated during piling in 1/3 octave-bands

Blue line – frequency spectrum without applying the weight function
Red line – frequency spectrum with the weigh function for marine mammals using high frequency range for echolocation
Orange line – frequency spectrum with the weight function for pinnipeds
Source: modification of NMFS (2016)

The sound levels within 1 m (the source levels) have been estimated on the basis of the sound exposure levels, which are the sound levels averaged within an interval of 1 second (measured in dB re 1 μPa^2·s units). The sound levels have been also given the atmospheric pressure levels (in dB re 1 μPa). These values have been estimated both for the single strike of a pile driver and for the series of strikes (cumulative/multiple strikes) within 1 hour of piling for one foundation. The key input parameters are:

- noise exposure level SEL for a single strike = 223,6 dB re 1 μPa^2·s;
- peak sound pressure level SPL_{peak} for a single strike = 243,6 dB re 1 μPa;
- cumulative noise exposure level SEL_{cum} in a period of 1 hour (2800 strikes) = 258.1 dB re 1 μPa^2·s.

After the application of the noise mitigation system, the noise levels assumed in the modelling will reach the following values:

- noise exposure level SEL for a single strike = 210,6 dB re 1 μPa^2·s;
- peak sound pressure level SPL_{peak} for a single strike = 230,6 dB re 1 μPa;
- cumulative noise exposure level SEL_{cum} in a period of 1 hour (2800 strikes) = 245.1 dB re 1 μPa^2·s.

3.2.2 Sound propagation modelling

The sound levels calculations in various distances from the sound source have been carried out for the frequency up to 2.5 kHz with the use of the numerical model of the underwater acoustic propagation. Above 2.5 kHz the noise decreases rapidly along with the distance due to the sound being attenuated by the sea water.

The sound propagation is determined with the use of the Range-dependent Acoustic Model (RAM). The RAM is based on the method of a parabolic equation assuming that the energy emitted dominates over the energy reflected. Therefore, the RAM calculates wave equations.

The underwater ambient noise modelling software MIKE UAS which is a part of the updated MIKE 2017 package has been used for numerical calculations. The model focuses on long-distance noise propagation in order to create the basis for carrying out environmental impact assessments of noise. The UAS applies a RAM code based on the sound propagation model developed by Collins (1993). The application of this element is responsible for the change of the sound attenuation rate and volume in a water column and enables the use of the empirical model of Francois and Garrison (1982a, 1982b) which is based on information regarding salinity, temperature and pH in a water column (3.1.1 and 3.1.2). Moreover, the UAS models the sound propagation in the seabed. The seabed characteristics are based on the constant density of the sediment and on the constant thickness of the sediments layer (3.1.3).

To approach the real impact of the seabed on the sound wave propagation in water, the sound waves absorption by the bed material should be taken into account. The applied model takes into account the sound propagation in the seabed, but applies only to oblong waves, not to resilient waves (in modelling seabed sediments are treated as fluids). Apart from taking into account the attenuation resulting from stratification of the seabed, the change of density at the water-seabed boundary is significant in a wave propagation research. Therefore, a simplified model of the seabed, based on stratification of the sediments depending on their density has been used. The lower boundary of a physical medium comprises an absorption layer which is a few wavelengths thick. This characteristic prevents a substantial amount of energy from bouncing off the lower boundary. The modelling covers the absorption layer and the comprehensive index of refraction model.

The sound source characteristics have been joined to the propagation model in order to calculate the sound propagation from the piling location in 72 2D transects to various directions. Specific 1/3 octave-bands with frequency ranged from 20Hz to 2.5 kHz which has the greatest significance for fish and marine mammals occurring in the area have been modelled. Based on the obtained calculations, maps presenting the sound exposure level as a function of a distance from the sound source have been prepared.

Due to the fact that marine biota uses the space in a whole water column, maximum sound levels calculated in a water column for each distance range have been presented.

The noise propagation modelling has been carried out with the assumption of the following simplified and specific conditions and presumptions:

- the water surface is treated as a simple, horizontal perfectly reflecting boundary, ignoring possible sea states where in addition to wave motion in the upper part of the water layer, an infusion of air bubbles occurs which has a significant impact on the speed of sound in the surface part of a water column;

- the MIKE UAS is a 2D model in which the substrate is made of layers with various acoustic characteristic. This assumption is applied in the case of areas with significant seabed diversification. However, the model does not take into account boulder areas and marine plants located on the seabed;
- the code of a 2D model ignores the 3D effects related to the horizontal refraction of the sound beam rays reflected from sloping seabed. In the case of a sloping beach and a continental slope around underwater mountains and islands the beam propagates obliquely along the slope and is subject to the phenomenon of horizontal refraction;
- in shallow waters the boundary constituted by the seabed plays a predominant role as propagating sound waves to a larger extent interact with the surface of water and the seabed due to the short distance between the two boundaries. When sound interacts with the seabed take place multiple times over short distances, the seabed structure becomes as significant as the area's depth. Therefore, the sound may propagate not only in a water column but also in sediments, resulting in the sound level attenuation due to the partial energy loss. When the seabed is made of unconsolidated sediments, resilient waves can be excluded in the modelling of sound interaction and propagation in the seabed. Therefore, only the effect of the compressed waves pressure has been modelled;
- the effects associated with acoustic background and masking have not been included in the model. For the frequency where the greatest part of the acoustic energy is concentrated, the acoustic background level is lower by around 100 dB, therefore it is assumed that it has insignificant impact on calculated results;
- the hammer's impact on a pile generates the sound moving down the pile and partially reflected upwards through both the seabed and the pile ending. In this modelling a single point enclosed source at the depth of 20 m (around the half of the depth of the examined area) is the source of noise. Due to a combination of the position of the noise source and the spring season along the seabed topography it is estimated that the sound propagation simulation will result in conservative estimates. In the spring season the noise source is located inside of an acoustic channel which enables the sound long- distance transmission;
- the effects associated with the near field (under 100 m from the noise source) are excluded as it is estimated that they will have a minimum impact on the sound level in the far field (over 100 m from the source of noise). For the impact zones included in this report (i.e. >100 m) the effects associated with the sound volume and the obliquely radiating waves predominant in the near field are significantly attenuated.

The accepted assumptions result in the conservative results of the sound levels calculations.

3.2.2.1 Numerical settings

The spatial discretisation used in the finite-differences model is defined in terms of the wavelength being modelled. Hence, the simulations take into account sensitivity to frequency components.

The depth resolution:

$$dz = \alpha\lambda$$

the radial resolution is defined as:

$$\mathrm{d}r = \beta\ \mathrm{d}z$$

when α determines the number of fractions in which the acoustic wave is split in a vertical direction. In the radial direction the spatial gradients are weaker in comparison to the vertical direction. β is used to relax the resolution of the propagation.

3.2.3 Sound attenuation in water

The sound attenuation in the sea water depends on the temperature, salinity, pressure and acidity (pH values) of water. In the Baltic Sea salinity (around 8 ppt) is over a half smaller than salinity in open waters of the ocean. The UAS models the sound attenuation in a water column with the use of the empirical model of Francois and Garrison (1982a, 1982b), in which the absorption coefficient is decomposed into three components, corresponding to the contributions of boric acid, magnesium sulphate and pure water (Lurton, 2010). More details, including the application of the equation, can be found in the Scientific Documents for UAS (DHI, 2017).

Low salinity of the Baltic Sea increased the absorption coefficient for low frequencies (below 500 Hz) and decrease it for high frequencies (above 1.25 kHz) in comparison to the forecast of the UAS for the standard salinity (35 PSU) and simplified model of Richards at al. (2013) (Figure 9).

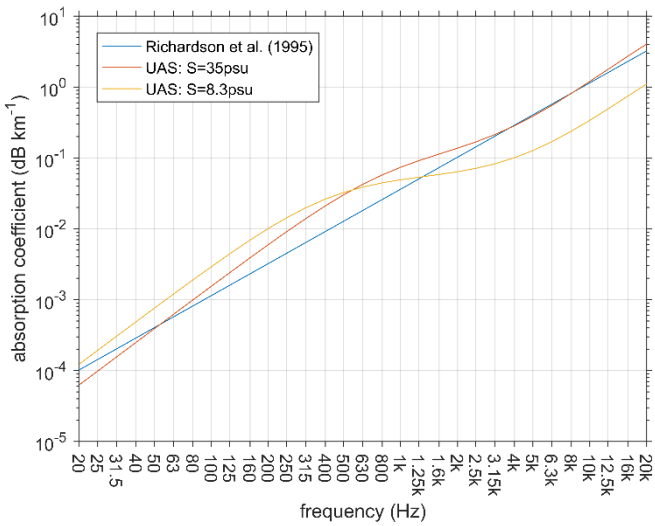

Figure 9. The absorption coefficient from the model of Francois and Garrison (1982a, 1982b) used in the MIKE UAS in comparison to the model of Richards et al. (1995)

The forecast in the MIKE UAS applies to the values pH 8 and T 3.1°C in the sound channel at the depth of around 50 m and salinity equal 35 PSU and 8.3 PSU
Source: internal data

3.2.4 Noise mitigation system

The noise mitigation system (Noise Mitigation System) helps with the decrease of the long-distance sound level. The most frequently used noise reduction systems include bubble curtains and screen of the company IHC Merwede (Bellmann, 2014). At the time of the implementation of the investment other technical measures might be available which would enable to achieve at least the same noise level as with the use of the bubble curtains. At the moment the investor does not declare which measures he will use but they will be at least as efficient as the bubble curtain.

The bubble curtain is a “wall” of air bubbles produced around a location where piling is carried out. The bubbles create an acoustic impedance mismatch which is an effective method of blocking the sound transmission (Spence et al., 2007). On the other hand, the IHC Merwede's sound level

reducing screen is an air-tight steel pipe surrounding large diameter piles. It has double walls filled with air and between them additional air bubbles can be feed-in between the large diameter pile and the steel pipe. The sounds, crossing through the air-filled double-wall steel screen, are reduced due to reflection caused by the impedance gap.

During the construction of the offshore wind farm Bokum West 2 in the North Sea (Diederichs et al., 2014) the effect of using a single bubble curtain Big Bubble Curtain (BBC) and a double bubble curtain Big Bubble Curtain (DBBC) was explored thanks to which reliable spectral data are available (Figure 10).

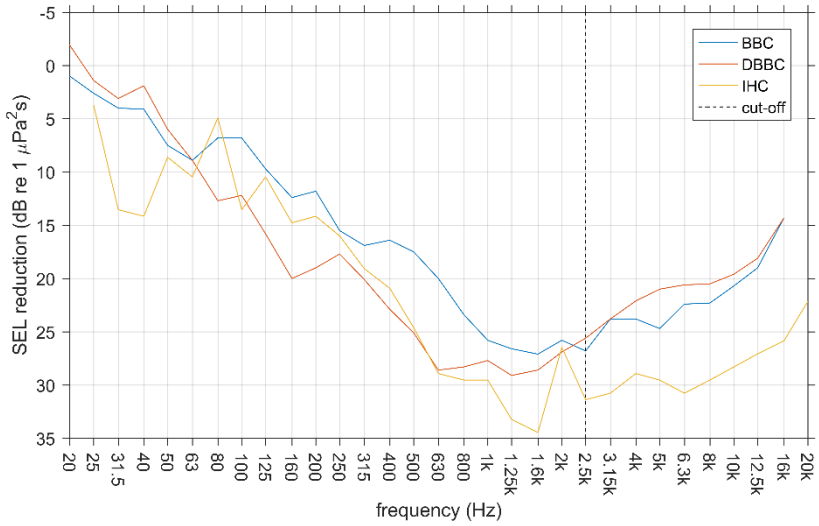

Figure 10. The SEL reduction in relation to the frequencies for the three various noise mitigation systems: the single bubble curtain Big Bubble Curtain (BBC), the double bubble curtain Big Bubble Curtain (DBBC) and the noise reduction screen IHC (IHC)

Source: internal data based on Diederichs et al. (2014) and data obtained from DONG Energy Wind Power A/S

Frequency dependant sound level decrease (Figure 10) is deducted from the source spectrum (Figure 8).

3.2.5 Cumulative sound exposure level

In order to define the biological impact of piling in terms of the acoustic "dose" not only the force of a single strike is considered but also the sound exposure level is determined from the "event" which is a series of strikes. If all strikes are the same, cumulative sound exposure level (SEL_{cum}) is defined according to the equation:

$$\mathrm{SEL_{cum}} = \mathrm{SEL} + 10\ \log_{10} n$$

where SEL corresponds to the exposure level of one strike, and *n* is the number of strikes.

The cumulative sound exposure level is based on 2800 strikes within 1 hour and results in the increase of the SEL value by 34.5 dB.

3.3 High frequencies transmission losses

The high frequency modelling requires an enormous calculating effort and it usually can be avoided because most of the spectral energy is below 2.5 kHz (3.2.1.1). After weighing high frequencies for cetaceans, most spectral energy ranges between 3.15 and 16 kHz (Figure 8). Therefore, all available

bands of high frequency sources up to 20 kHz should be taken into consideration. The transmission loss in the high frequency bands have been estimated based on the results of the low frequency model. The lower frequency, the larger extent of the sound waves interactions with the seabed and the high transmission losses hamper propagation. While the impact of the sea-bed topography decreases as the frequency increases, the sound attenuation intensifies, hence between the transmission loss resulting from the sea-bed topography and the sound attenuation resulting from the transmission loss – a minimum transmission loss occurs.

After the modelling of the minimum transmission loss, each transmission loss calculated beyond this frequency band serves as the first conservative assessment of the transmission loss for even higher frequency bands. For more realistic estimation, the increase of the sound attenuation included in the model of Francois and Garrison (1982a, 1982b) is added in order to obtain a conservative estimate. Predicting some model results, the estimated loss within high frequency transmission for the Baltica 2 Area has been presented (Figure 11).

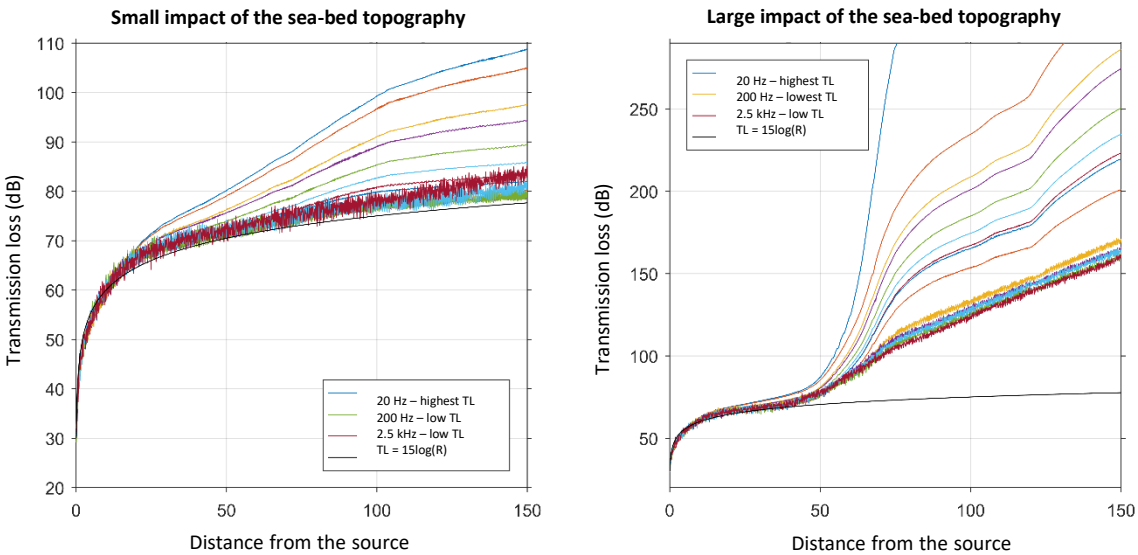

Figure 11. Transmission loss from the simulation MIKE UAS in two transects selected from the Baltica 2 Area

Left side: transect No. 2 and small impact of the sea-bed topography
Right side: transect No. 1 and large impact of the sea-bed topography
All transmission losses are the minimum values in a given distance from the source. The graphs present only selected elements of the spectrum
Source: internal data

The sound spreading along the transect No. 2 in the Baltica 2 Area is almost unimpeded but low frequencies still have increased transmission loss due to the seabed topography (Figure 11). Third octave with the central frequency of 20 Hz is subject to the greatest transmission losses. The transmission loss increases along with the frequency and reaches the lowest value at the frequency of 250 Hz. Then it increases again up to the frequency of 2.5 kHz, the last modelled band. With further increase of the frequency, due to the increased sound attenuation it can be assumed that the transmission loss in the band of 2.5 kHz constitutes a conservative estimate for all higher frequencies.

If the impact of the sea-bed topography is significant like in the case of the transect 1, the transmission loss is much more intense, even in the lower frequency bands (Figure 11). The transmission losses decrease significantly when the frequency increases to 200 Hz and then stabilize

itself. Therefore, the transmission loss at 2.5 kHz can still serve as an estimate for even higher frequencies, even if it is not as conservative as in the case of a small impact of the sea-bed topography.

The transmission loss at the frequency of 2.5 kHz constitutes the base for the transmission losses at higher frequencies and includes the loss caused by the impact of the sea-bed topography of a marine area. The increase of the sound attenuation predicted by the model of Francois and Garrison (1982a, 1982b) has been added to this basic transmission loss. In the conservative approach, the sound attenuation resulting from the parameters of the sound channel condition is applied (Figure 9, yellow line). The consequential transmission loss for a full frequency spectrum shows a smooth transition from the numerical model to the high frequency extrapolation (Figure 12).

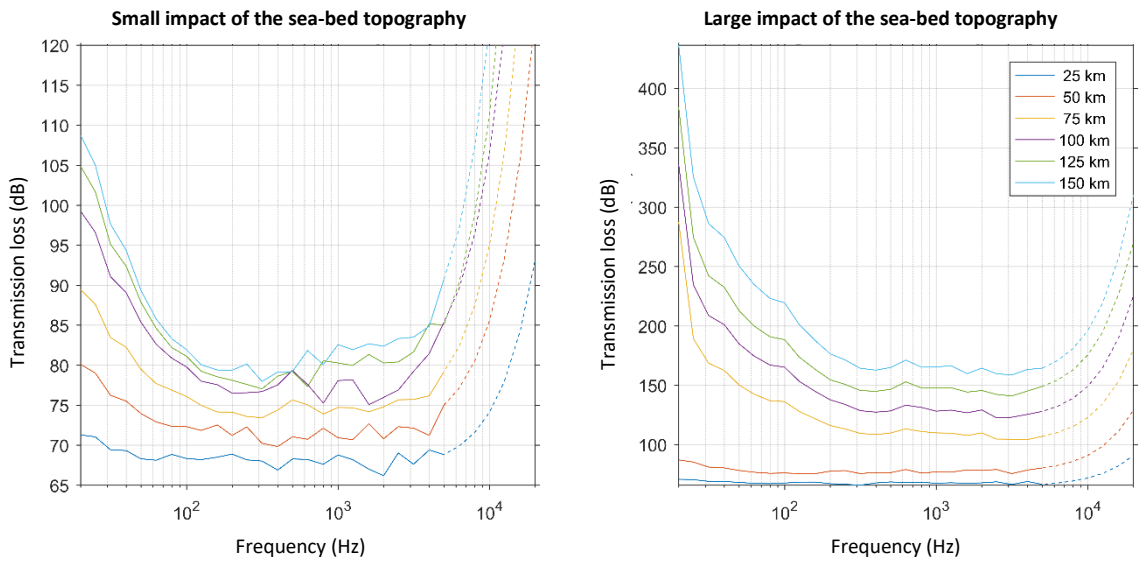

Figure 12. Spectrum transmission loss after extrapolation along two selected transects in the Baltica 2 Area

Left side: Transect No. 2 and small impact of the sea-bed topography
Right side: transect No. 1 and large impact of the sea-bed topography
Continuous lines represent the results of the MIKE UAS simulation and dotted lines indicate the extrapolated part. All transmission losses are minimum values in a given distance from the source. The graphs present the impact of the losses only at selected distances
Source: internal data

The estimation of the transmission loss in high frequencies will be applied during the consideration of the weighted sound levels for the marine biota such as seals or porpoises.

3.4 Threshold values

The impact of noise on marine biota may be divided into five broad categories which to a large extent depend on the distance of a specific individual from the sound source (Richardson et al., 2013):

- sound detection;
- masking;
- behavioural reactions (such as avoidance);
- hearing threshold shift (TTS, PTS).

The NOAA has formulated recommendations regarding causing the PTS and the TTS in classes of marine mammals and fish differing in terms of their hearing characteristics (Southall et al., 2007).

Their criteria are based on the weight function previously not used (Table 3). These criteria are perceived as the most comprehensive and in such a way they have been applied in the assessment.

Table 3. The criteria for noise exposition applied when calculating the impact range

Source	Impact	Taxonomic group	Modelled sound type	SEL
NMFS, 2016	PTS	Harbour porpoise	Single strike and accumulated impact [1 hour]	155 dB re 1 μPa²s
	TTS	Harbour porpoise	Single strike and accumulated impact [1 hour]	140 dB re 1 μPa²s
	PTS	Harbour seal	Single strike and accumulated impact [1 hour]	185 dB re 1 μPa²s
	TTS	Harbour seal	Single strike and accumulated impact [1 hour]	170 dB re 1 μPa²s
Maxon et al., 2015	Behavioural reaction	Harbour porpoise	Single impact	140 dB re 1 μPa²s (non-weighted SEL)
Russel et al., 2016	Behavioural reaction	Harbour seal	Single impact	158 dB re 1 μPa²s (non-weighted SEL)
Popper et al., 2014	PTS	Fish without swim bladders	Single strike and accumulated impact [1 hour]	216 dB re 1 μPa²s
Popper et al., 2014	PTS	Fish with swim bladders	Single strike and accumulated impact [1 hour]	203 dB re 1 μPa²s
Popper et al., 2014	TTS	Fish without swim bladders	Single strike and accumulated impact [1 hour]	186 dB re 1 μPa²s
Popper et al., 2014	TTS	Fish with swim bladders	Single strike and accumulated impact [1 hour]	186 dB re 1 μPa²s
Hawkins i in., 2014	Behavioural reaction	Fish without swim bladders	Single impact	142 dB re 1 μPa²s (non-weighted SEL)
Hawkins i in., 2014	Behavioural reaction	Fish with swim bladders	Single impact	135 dB re 1 μPa²s (non-weighted SEL)

Source: modification of NOAA (2016), Russel et al., (2016), Maxon et al. (2015), Popper et al. (2014), Hakins et al. (2014)

4 Modelling of noise propagation as a result of a single location piling

The noise impact range has been determined on the basis of the modelling of the noise propagation as a result of a single location piling taking into consideration the noise mitigation system. All calculations of the noise propagation demonstrated in the further part of this section take into consideration the use of the noise mitigation system.

4.1 Sound levels

The transmission loss (TL) within the frequency of 1/3 octave-band is a standard result of the noise propagation modelling.

$$\mathrm{TL_f} = -20\log_{10}\frac{\mathrm{p_{recived}}}{\mathrm{p_{source}}}$$

The transmission loss means a cumulative decrease of the acoustic pressure because the acoustic pressure wave spreads outside from the source. Therefore, the loss of transmission from the source to the receiver is defined in an equation in which the upper index R means a receiver and the upper index SRC means the source.

$$\mathrm{SEL}^{\mathrm{R}} = \mathrm{SEL}^{\mathrm{SRC}} - \mathrm{TL}$$

Given that the transmission loss is dependent on the frequency, the received sound level is calculated on 1/3 octave-band, and additionally the overall level of the sound received is determined on the basis of an equation in which $\mathrm{SEL}_f^{\mathrm{SRC}}$ constitutes the SEL for each 1/3 octave-band with a central frequency f.

$$\mathrm{SEL}_{\mathrm{oa}}^{\mathrm{R}} = 10\log_{10}\left(\sum_f 10^{0.1\ \mathrm{SEL}_f^{\mathrm{SRC}} - 0.1\ \mathrm{TL}_f}\right)$$

The SEL level obtained from the above equation has been used for defining the total transmission loss.

$$\mathrm{TL}_{\mathrm{oa}} = \mathrm{SEL}_{\mathrm{oa}}^{\mathrm{SRC}} - \mathrm{SEL}_{\mathrm{oa}}^{\mathrm{R}}$$

The total transmission loss may be used to define obtained values $\mathrm{SPL}_{\mathrm{peak}}$ and $\mathrm{SPL}_{\mathrm{rms}}$.

$$\mathrm{SPL}^{\mathrm{R}} = \mathrm{SPL}^{\mathrm{SRC}} - \mathrm{T}_{\mathrm{oa}}$$

The above is applicable on the assumption that the shape of the frequencies SEL and SPL spectra is the same.

4.1.1 Weighing

Marine mammals are divided into various functional groups in terms of their hearing features. Various hearing features – expressed as a range in which specific species can hear – is measured quantitatively by the NMFS (2016) by frequencies weighing and expressed as:

$$(f) = C + 10\log_{10}\left(\frac{(f/f_1)^{2a}}{\left[1+(f/f_1)^2\right]^a\left[1+(f/f_2)^2\right]^b}\right)$$

where parameters a, b and C and frequencies: f_1 and f_2 are listed in the table below (Table 4). The weighing curves are presented in the figure below (Figure 13). The hearing range has been provided in the table (Table 4).

The weighted level of the sound impact exposure is determined by weighing each frequency band.

$$\mathrm{SEL} = 10\log_{10}\left(\sum_f 10^{0.1\ \mathrm{SEL}_f - 0.1\ W(f)}\right)$$

Table 4. Functional hearing groups and associated with them hearing channels

Functional hearing groups	**General hearing range**	a	b	f_1 **(kHz)**	f_2 **(kHz)**	C **(dB)**
Cetaceans emitting high-frequency sounds (HF) – harbour porpoises	275 Hz–160 kHz	1.8	2	12	140	1.36
Pinnipeds in water (PW) – seals	50 Hz–86 kHz	1.0	2	1.9	30	0.75

Source: modification of NMFS (2016)

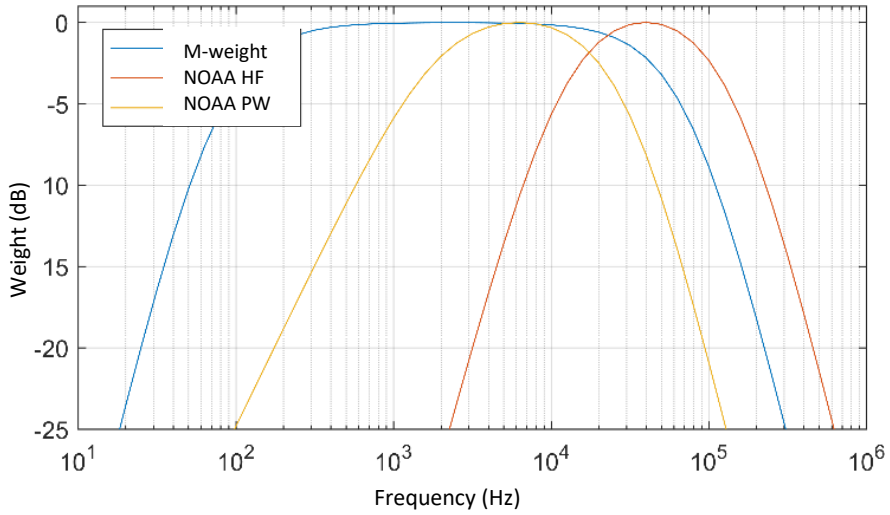

Figure 13. The applied HF and PW weights in comparison to the M-weight for marine mammals in water

The area is modelled only to 2.5 kHz, the transmission loss between 3.15 and 20 kHz is estimated on the basis of the modelled loss in transmission of the low frequency sound

Source: internal data based on ESPOO REPORT (2016)

4.2 Results of the numerical modelling of propagation of sound generated in the Baltica 2 Area

4.2.1 Sound propagation model in the case of a single strike of a pile driver

The sound exposure level during a single strike of a pile driver reaches the maximum value at the sound source and drops to the value of 60 dB and below in the areas of the acoustic shadow caused by the small depths. The noise exposure level does not exceed 145 dB at the boundaries of the modelled area, located at the distance of 150 km from the source (Figure 14).

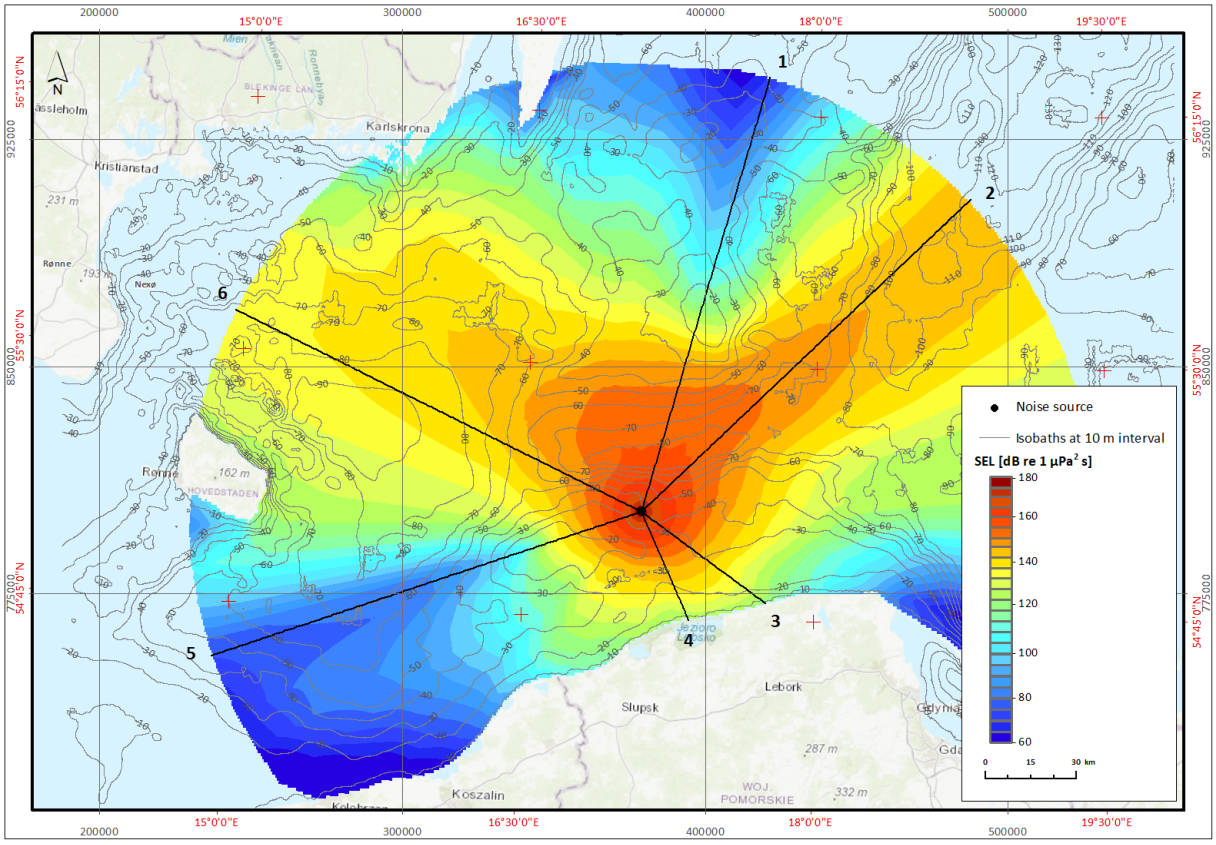

Figure 14. The acoustic map of the noise exposure level SEL (dB re 1 µPa^{2}s) caused by a single strike of a pile driver in the Baltica 2 Area

The lines present the described transects

Source: internal data

The sound propagation model indicates two main directions (channels) of the sound spreading – north-eastern (transect 2) and north-western (transect 6), where in the north-eastern channel higher sound levels have been observed. Between the two above mentioned channels in the north direction (transect 1) and along the coastal line in the south of the model area (transect 5) the shallowing of the sea area exacerbates the sound propagation conditions and makes the SEL level decrease significantly. In the south and south-eastern direction from the modelled sound source – the Polish coast is located at a distance shorter than 50 km and is affected by the sound wave with the exposure level SEL around 120 dB (transects 3 and 4).

The impact of the sea-bed topography in a sea area on the sound propagation conditions is reflected by the diagram below (Figure 15) in which the sound spreading along the transect 1 has been illustrated. Directly from the source the sound propagates mainly along the trajectory directed downwards an undersea valley, by which indicating that the underwater sound channel is both shaped by the thermohaline conditions (profile of the sound velocity) and limited by the upper and lower boundary i.e. respectively – the surface of the sea and the seabed. The sound spreads along the main trajectory towards the shallows located at a distance of around 70 km from the source, then “heads” down the next valley. The large gradient of the SEL value within the shallows in this way indicates the increase of the transmission losses caused by the decrease of the depth.

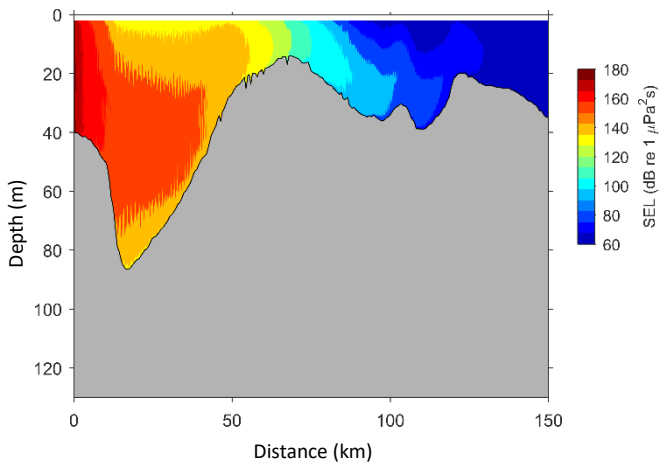

Figure 15. The model of the sound propagation along the transect 1 – the sound exposure level SEL (dB re 1 μPa^2·s) for a single strike of a pile driver

Source: internal data

The model of sound propagation along the transect 2 has been illustrated on the diagram below (Figure 16). In contrast to the situation considered above regarding transect 1, in this case the sound, almost unimpeded, spreads from its source located at the depth of 20 m in the direction of an axis of the underwater sound channel located at the depth of around 45 m. At longer distances (over 50 km) from the source, the low frequency vertical structure of the sound field becomes clearly notable. The sound attenuation caused by a small interaction with the seabed occurs to a small degree. This leads to the higher SEL values on the edge of the model's range (around 150 km from the source).

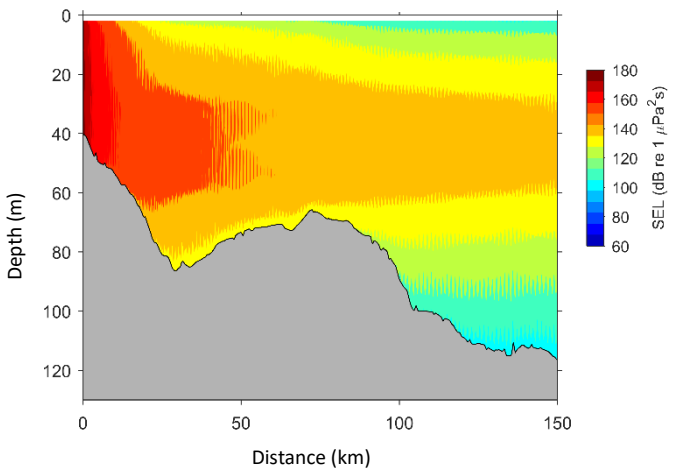

Figure 16. The sound propagation model along the transect 2 – noise exposure level SEL (dB re 1 μPa^2·s) in the case of a single strike of a pile driver

Source: internal data

The sound which propagates along the transect 3 (Figure 17), reaches the highest sound exposure level along the coast and slightly higher along the transect 4 located in the coastal zone and constituting the shortest section between the source and the coast (Figure 18). Both transects: 3 and

4 show that the coast is quite steep and the depth of water equals at least 15 m which enables the sound propagation. However, the water depth along the transect 3 is greater than along the transect 4 which results in the higher level of the sound exposure in the coastal zone in spite of the fact that the distance from the source is longer.

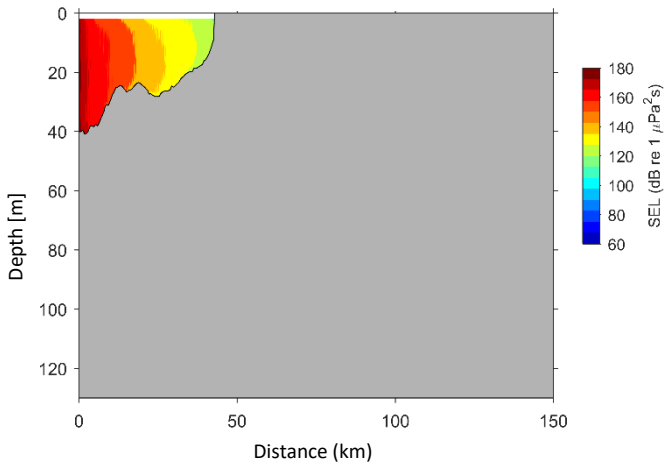

Figure 17. The model of the sound propagation along the transect 3 – the sound exposure level SEL (dB re 1 μPa^2·s) for a single strike of a pile driver

Source: internal data

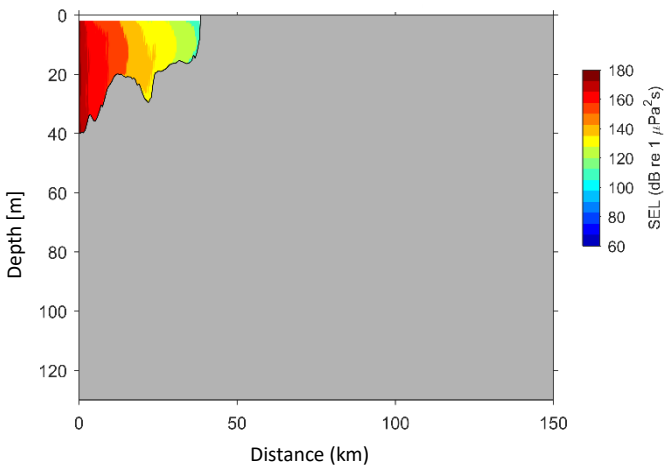

Figure 18. The model of the sound propagation along the transect 4 – the sound exposure level SEL (dB re 1 μPa^2·s) for a single strike of a pile driver

Source: internal data

The sound propagation along the transect 5 (Figure 19) is similar to the one occurring along the transect 1 (Figure 15) but characteristics of the transmission loss in the shallows area are even more evident. Due to small depths within the first 30 km from the source, the transmission loss expressed with the SEL gradient is large and reaches the maximum at the threshold. A shallow water column above the threshold acts as a new but weak sound propagation source in the area at the distance of

over 50 km from the primary source. The sound propagates along the seabed until it reaches the sound channel where it propagates further at the lower vertical structure.

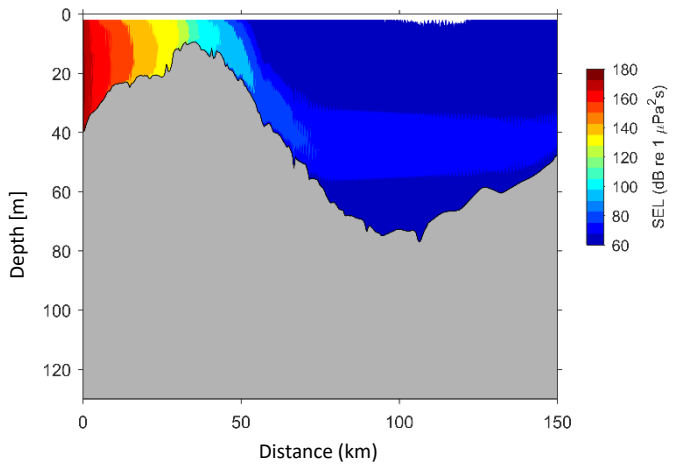

Figure 19. The model of the sound propagation along transect 5 – the sound exposure level SEL (dB re 1 μPa^2·s) for a single strike of a pile driver

Source: internal data

Transect 6 (Figure 20) is comparable to transect 2 (Figure 16) but unimpeded propagation will occur along with the increase of the water depth to over 50 m, at the distance of around 25 km from the source. The sound reaching the sound channel spreads within the vertical structure in a low frequency mode. The maximum SEL is located at a shorter distance than in the case of transect 2 due to the shallows in the vicinity of the source.

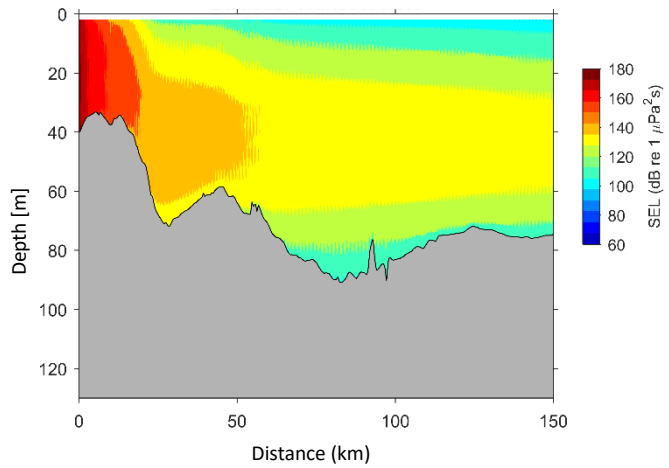

Figure 20. The model of the sound propagation along transect 6 – the sound exposure level SEL (dB re 1 μPa^2·s) for a single strike of a pile driver

Source: internal data

The direct comparison of the curves reflecting the maximum SEL values along all 6 transects designated on the acoustic map illustrates the impact of the depth on the transmission loss (Figure

21). The lack of obstacles (terrain-based) at the sound propagation along transect 2 corresponds to the transmission loss TL expressed with the equation below:

$$\mathrm{TL} = 15\log_{10}(R/R_0)$$

where:

R – the distance from the source,

R_0 = 1 m – the reference distance.

The logarithmic form of the transmission loss TL is a generally accepted approximation and constitutes evidence of the MIKE UAS's applicability in this specific case. The conditions of the sound propagation along transect 6 (light blue line) are characterized by greater losses during propagation along the first 30 km from the source but further away they react according to the logarithmic description and the curve of the noise exposure level runs in parallel with the SEL predicted for transect 2 (orange line). The sound propagation of a similar nature occurs along transect 5 (green line) with free conditions of the sound propagation starting at the distance of around 75 km from the source. On the other hand, for transects 1, 3 and 4 – increased transmission losses occur along the whole length of these transects. The conditions of the sound propagation along transect 3 (yellow line) are characterized by the greatest SEL values along the coastal line and are slightly higher than the values along transect 4 (purple line) corresponding to the shortest distance between the sound source and the coast. The depth profiles along both transects: 3 and 4 show that the coast is quite steep and the depth of water near the coast is at least 15 m which enables favourable conditions of the sound propagation. However, the depth of water along transect 3 is generally greater than along transect 4, which is the reason for higher SEL values observed at the coast in spite of the longer distance.

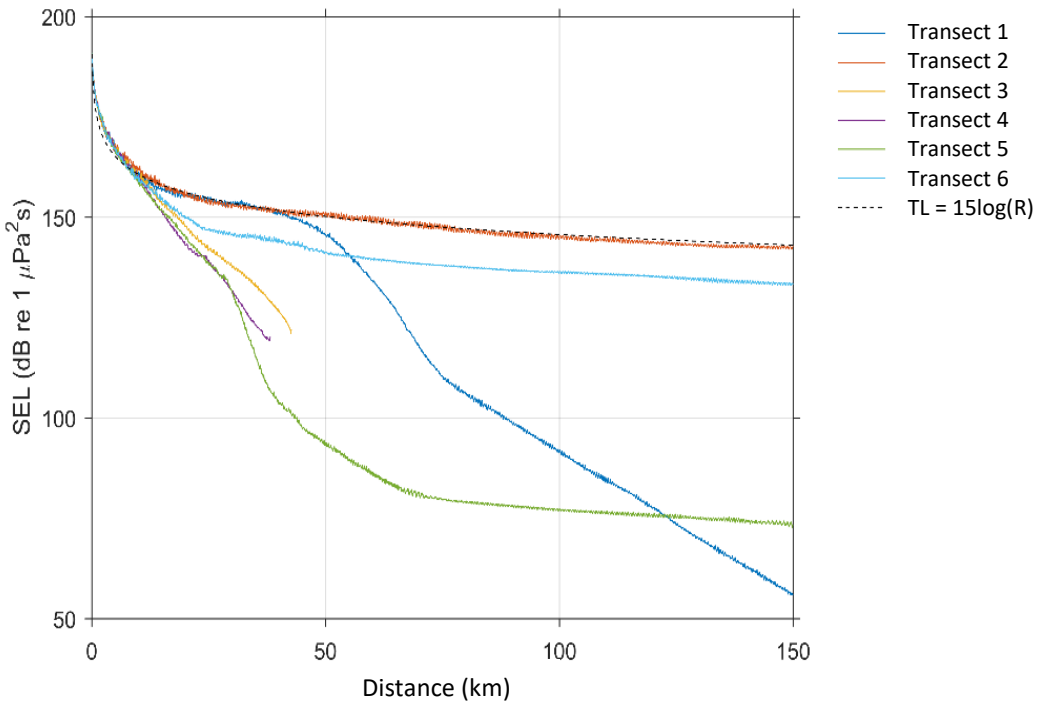

Figure 21. The summary of the maximum SELs during a single strike with a pile driver along designated transects

Source: internal data

4.2.2 Impact range

4.2.2.1 Grey and harbour seals

The impact range for the behavioural reaction amounted to 4.5 km in all directions (Figure 22, green line). The impact ranges for the TTS for the sound exposure level resulting from a single strike with a pile driver and for the cumulative sound exposure level resulting from a multiple (1-hour long) strikes with a pile driver on average amounted to 0.1 km for the single strike and 5.6 km for multiple strikes and the maximum range amounted to 0.1 and 6.7 km respectively (Figure 22, orange line). The impact range for the PTS is smaller than the TTS and shows an almost round shape around the source with the distance not exceeding 0.1 km for the single strike and 0.8 km for the cumulative (1 hour) strike of a pile driver (Figure 22, red line). The average PTS impact range in all directions amounts to respectively: 0.1 km for the single and 0.7 km for the cumulative SEL. For maximum SPL values (Figure 23) all impact ranges are below 0.1 km. A summary of the impact ranges from the source have been presented in the table below (Table 5).

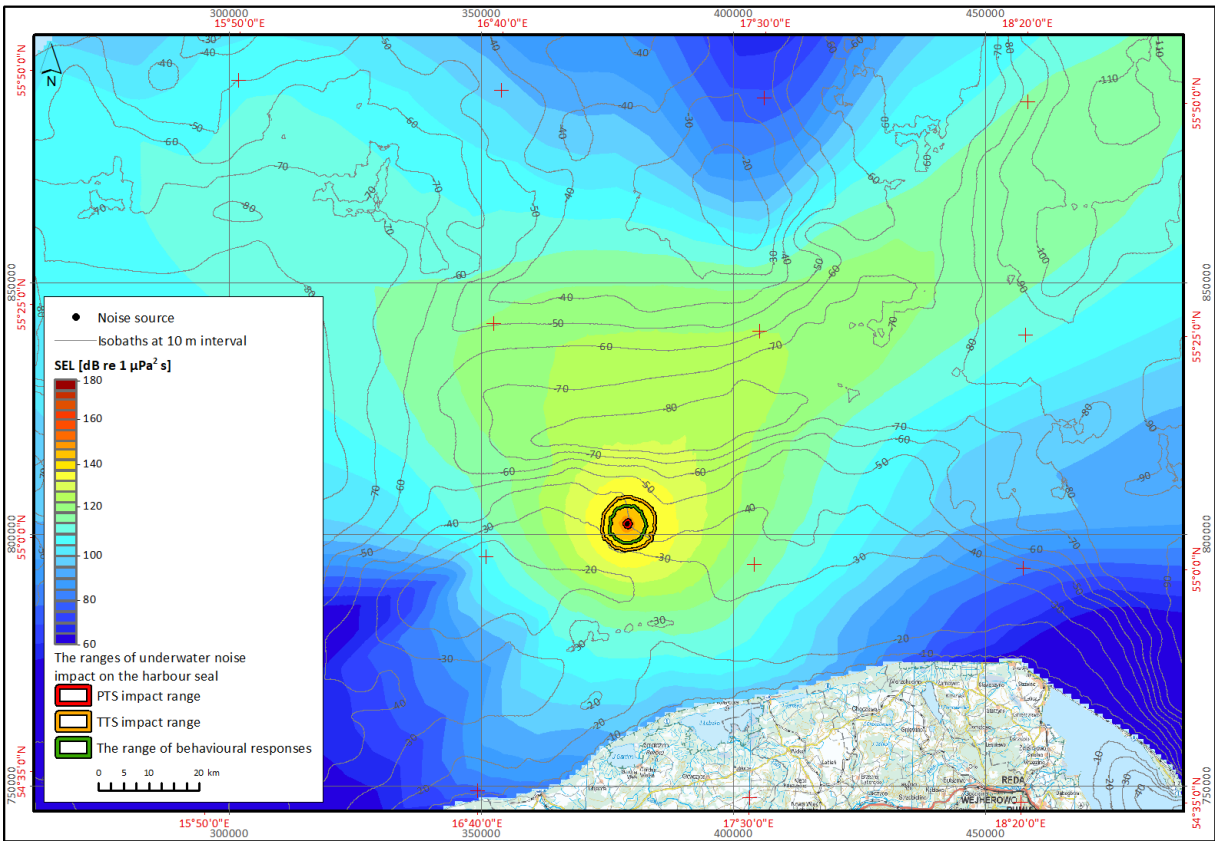

Figure 22. The acoustic map of the weighted (PW) noise exposure level SEL (dB re 1 µPa^{2}s) caused by a single strike of a pile driver in the Baltica 2 Area

The ranges of the TS and the PTS impacts based on SEL_{cum}

Source: internal data

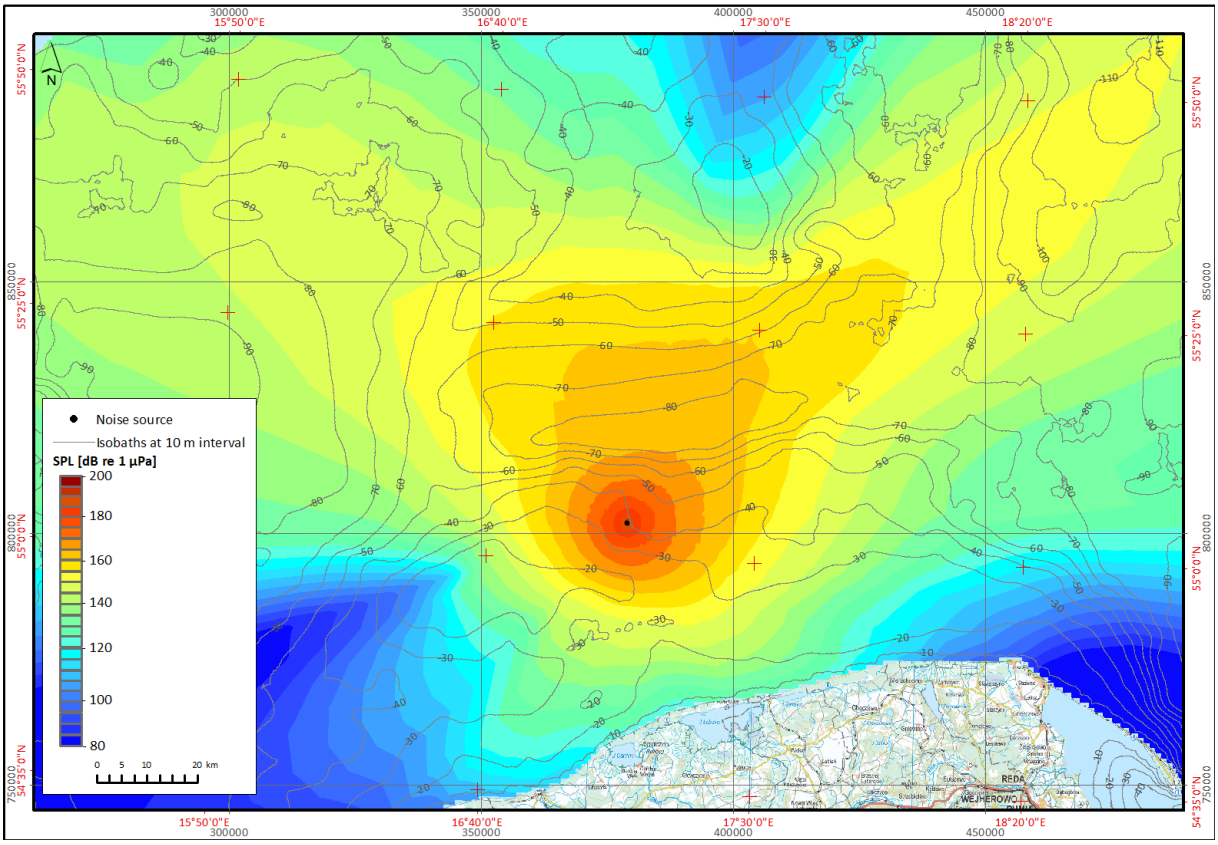

Figure 23. Acoustic map of the sound pressure level SPL_{peak} in the Baltica 2 Area

The PTS, TTS impact and the behavioural reaction range (<0.1 km) has been depicted with the use of the black spot in the noise source location

Source: internal data

Table 5. The noise impact range in the case of grey and harbour seals

Threshold value	SEL [dB re 1 µPa²s]	Average distance [km]	Maximum distance [km]	SPL_{peak} (dB re 1 µPa)	Average distance [km]	Maximum distance [km]
Behavioural reaction	158	4.0	4.5	212	0.1	0.1
TTS (a single pile driver strike)	170	0.1	0.1	212	0.1	0.1
TTS (cumulated impact [1 hour])	170	5.6	6.7	-	-	-
PTS (a single pile driver strike)	185	0.1	0.1	218	0.1	0.1
PTS (cumulated impact [1 hour])	185	0.7	0.8	-	-	-

The PW weight has been applied in the case of the SEL for the TTS and the PTS values. The weight has not been applied in the case of the SPL_{peak} and behavioural reactions

Source: internal data

4.2.2.2 Porpoises

Due to the lower threshold values for porpoises in comparison to seals, the impact ranges (Figure 24, Figure 25) are wider. The impact ranges in the form of the behavioural reactions do not exceed the modelling range. The impact range for the behavioural reactions amounts to 13.4 in all directions

where the sea-bed topography constitutes an obstacle for the sound propagation but extends to 46 km in the north east due to the sound channel (Figure 24, green line). The average range amounts to 22.8 km. The average range for the TTS amounts to 1.2 for the SEL and 18.5 SEL_{cum}, and the maximum is 1.8 and 26.3 km respectively (Figure 24, orange line). The impact ranges for the PTS are smaller than the ranges for the TTS and show an almost round shape around the source with the maximum radius not exceeding 0.1 km for the SEL and 9.4 km for the SEL_{cum} (Figure 24, red line). The average PTS impact range in all directions amounts to respectively: 0.1 km and 7.9 km.

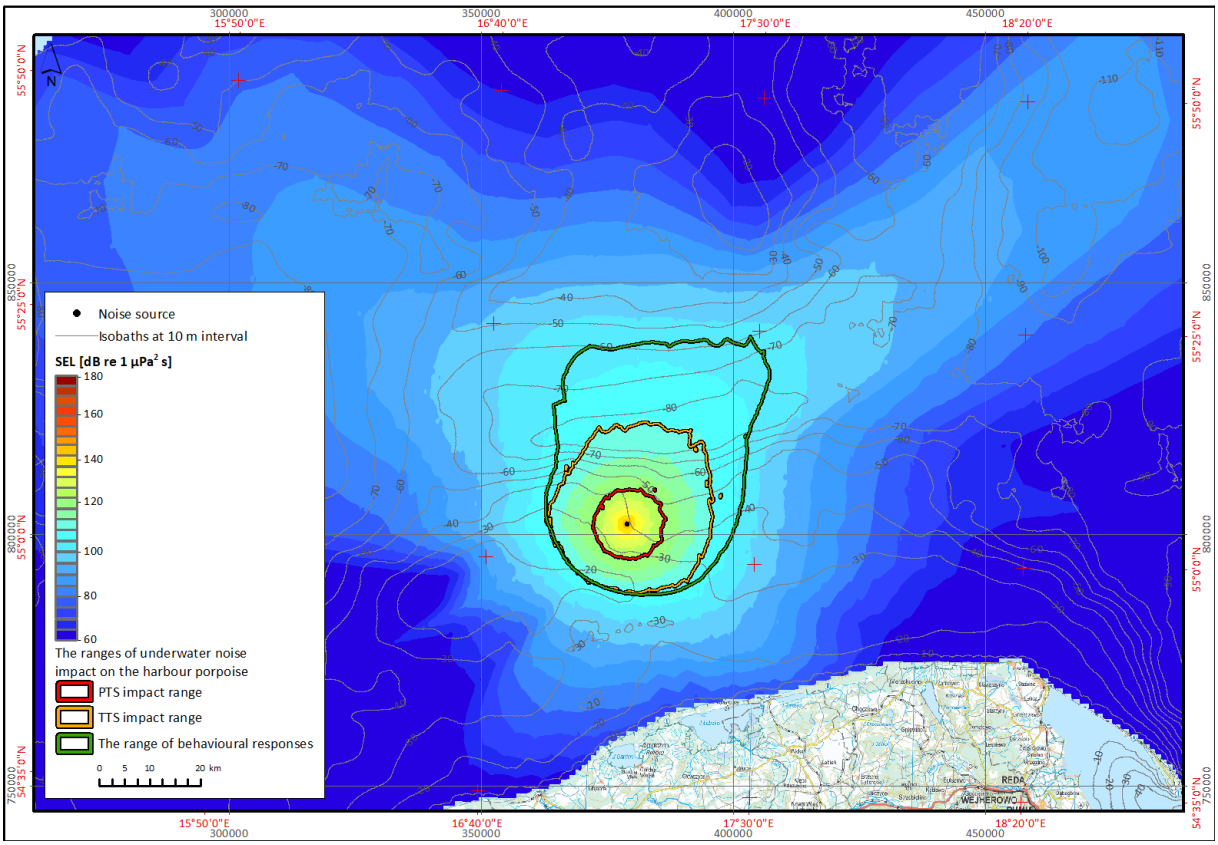

Figure 24. The acoustic map of the weighted (HF) noise exposure level SEL (dB re 1 µPa²s) caused by a single strike of a pile driver in the Baltica 2 Area

The ranges of TTS and PTS impacts based on SEL_{cum}
Source: internal data

The ranges SPL_{peak} (Figure 25) are available only for the TTS and PTS and are below the impact ranges based on the SEL. The impact ranges for the TTS and the PTS are circular in shape and have a constant radius of 0.2 and 0.1 km respectively. A summary of the impact ranges from the source have been presented in the table below (Table 6).

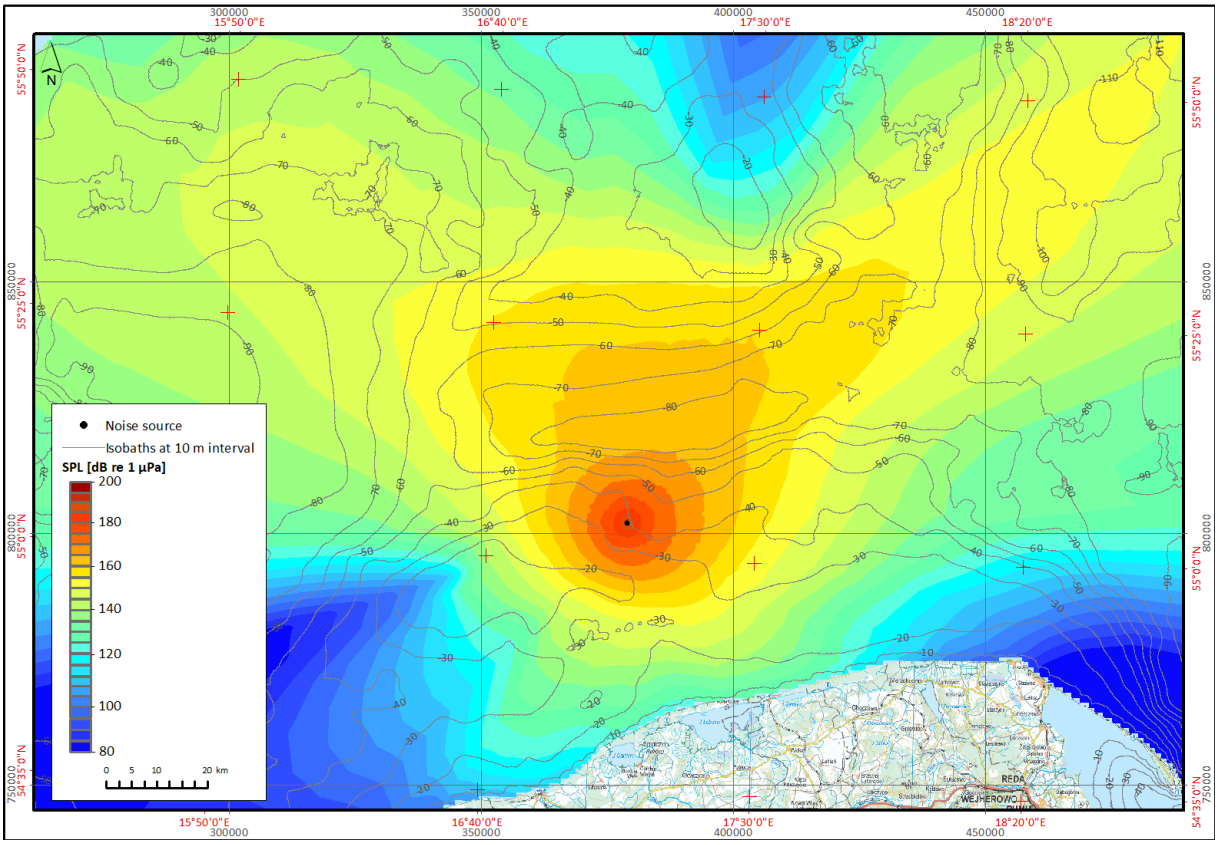

Figure 25. Acoustic map of the sound pressure level SPL_{peak} taking into account the threshold values in the Baltica 2 Area

The PTS and the TTS impact as well as the behavioural reaction range (<0.1 km) has been depicted with the use of the black spot in the noise source location
Source: internal data

Table 6. The impact ranges in the case of porpoises.

Threshold value	SEL [dB re 1 µPa²s]	Average distance [km]	Maximum distance [km]	SPLpeak (dB re 1 µPa)	Average distance [km]	Maximum distance [km]
Behavioural reaction	140	22.8	46.0	--	--	--
TTS (a single pile driver strike)	140	1.2	1.8	196	0.2	0.2
TTS (cumulated impact [1 hour])	140	18.5	26.3	--	--	--
PTS (a single pile driver strike)	155	0.1	0.1	202	0.1	0.1
PTS (cumulated impact [1 hour])	155	7.9	9.4	--	--	--

The HF weight has been applied in the case of the SEL for the TTS and PTS values. The weight has not been applied in the case of the SPL_{peak} and behavioural reactions
Source: internal data

4.2.2.3 Ichthyofauna

The TTS and PTS impact ranges for fish with and without the swim bladder are calculated on the basis of the exposure level to noise caused by a single strike of a pile driver and cumulative sound

exposure level resulting from multiple strikes (within 1 hour). The SEL_{cum} is higher than the SEL for a single strike by 34.5 dB. The PTS impact range based on the SEL caused by a single strike of a pile driver is smaller than 100 m due to the high threshold values for fish with and without the swim bladder. The sampling interval of the model was 100 m therefore the smallest calculated impact range was 0.1 km.

The impact ranges for fish with the swim bladder have been provided in the table (Table 7) and the modelling results have been demonstrated in the diagram below (Figure 26).

Table 7. The impact ranges in the case of fish without the swim bladder

Threshold value	SEL [dB re 1 µPa²s]	Average distance [km]	Maximum distance [km]
Behavioural reaction	142	18.6	32.6
TTS (a single pile driver strike)	186	0.1	0.1
TTS (cumulated impact [1 hour])	186	8.0	9.2
PTS (a single pile driver strike)	216	0.1	0.1
PTS (cumulated impact [1 hour])	216	0.1	0.1

The threshold value applies to the sound exposure level without taking into account the weight
Source: internal data

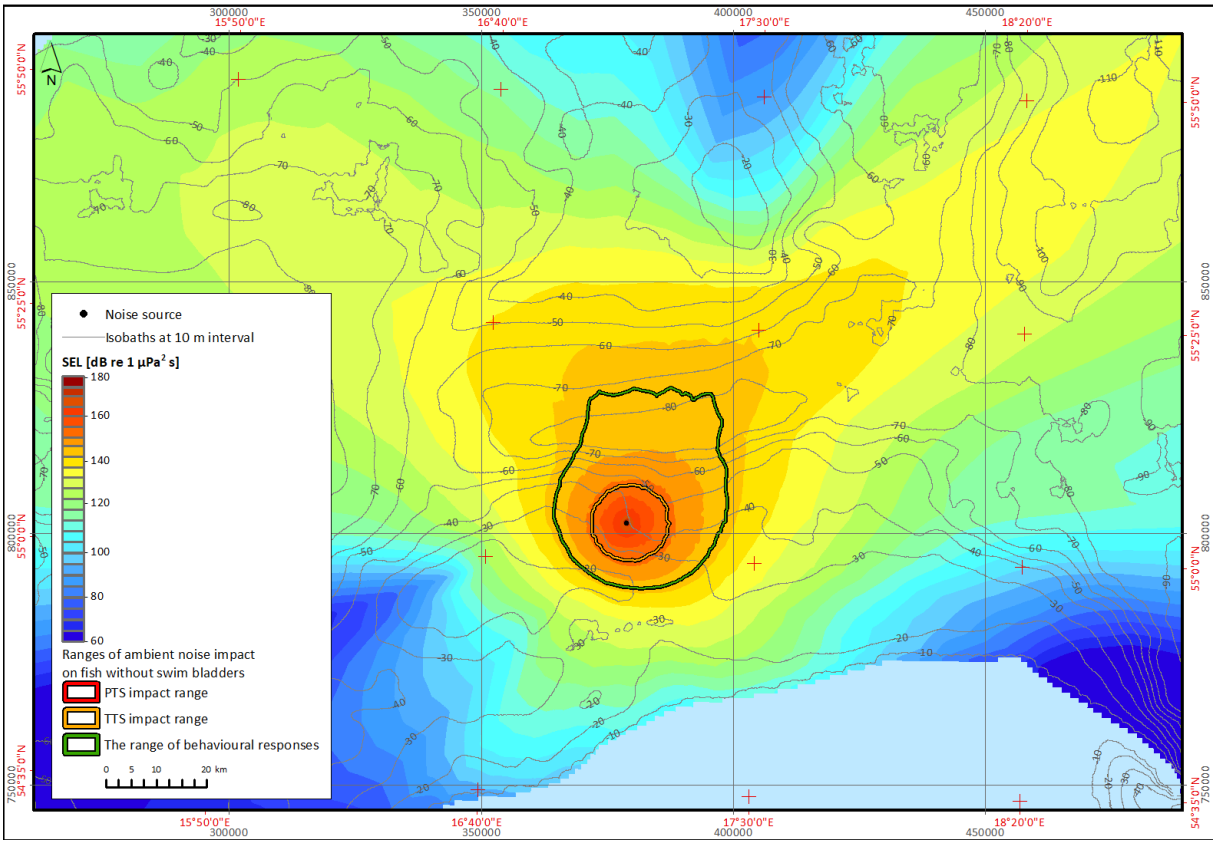

Figure 26. The acoustic map of the noise exposure level SEL (dB re 1 µPa²s) caused by a single strike of a pile driver in the Baltica 2 Area in the case of fish without the swim bladder

The ranges of TTS and PTS impacts based on SEL_{cum}
Source: internal data

The impact ranges for fish with the swim bladder have been provided in the table (Table 8) and the modelling results have been demonstrated in the diagram below (Figure 27).

Table 8. The impact ranges in the case of fish with the swim bladder

Threshold value	SEL [dB re 1 µPa²s]	Average distance [km]	Maximum distance [km]
Behavioural reaction	135	31.7	76.2
TTS (a single pile driver strike)	186	0.1	0.1
TTS (cumulated impact [1 hour])	186	8.0	9.2
PTS (a single pile driver strike)	203	0.1	0.1
PTS (cumulated impact [1 hour])	203	0.9	1.0

The threshold value applies to the sound exposure level without taking into account the weight
Source: internal data

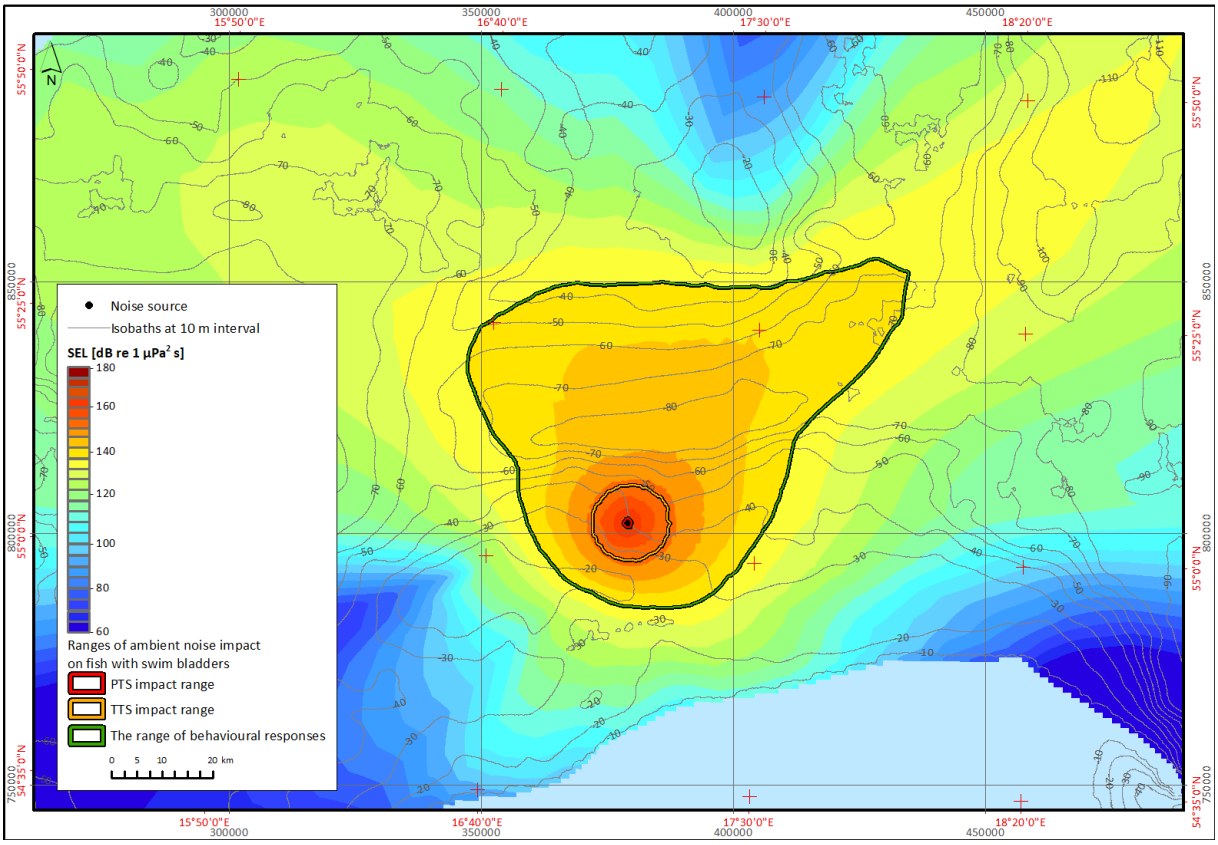

Figure 27. The acoustic map of the noise exposure level SEL (dB re 1 µPa²s) caused by a single strike of a pile driver in the Baltica 2 Area in the case of fish with the swim bladder

The ranges of TTS and PTS impacts based on SEL_{cum}
Source: internal data

4.3 Results of the numerical modelling of the propagation of sound generated in the Baltica 3 Area

4.3.1 Sound propagation model in the case of a single strike of a pile driver

The sound exposure level during a single strike of a pile driver reaches the maximum value at the sound source and drops to the value of 60 dB and below in the areas of the acoustic shadow caused

by the small depths. The noise exposure level does not exceed 140 dB at the boundaries of the modelled area, located at the distance of 150 km from the source (Figure 28).

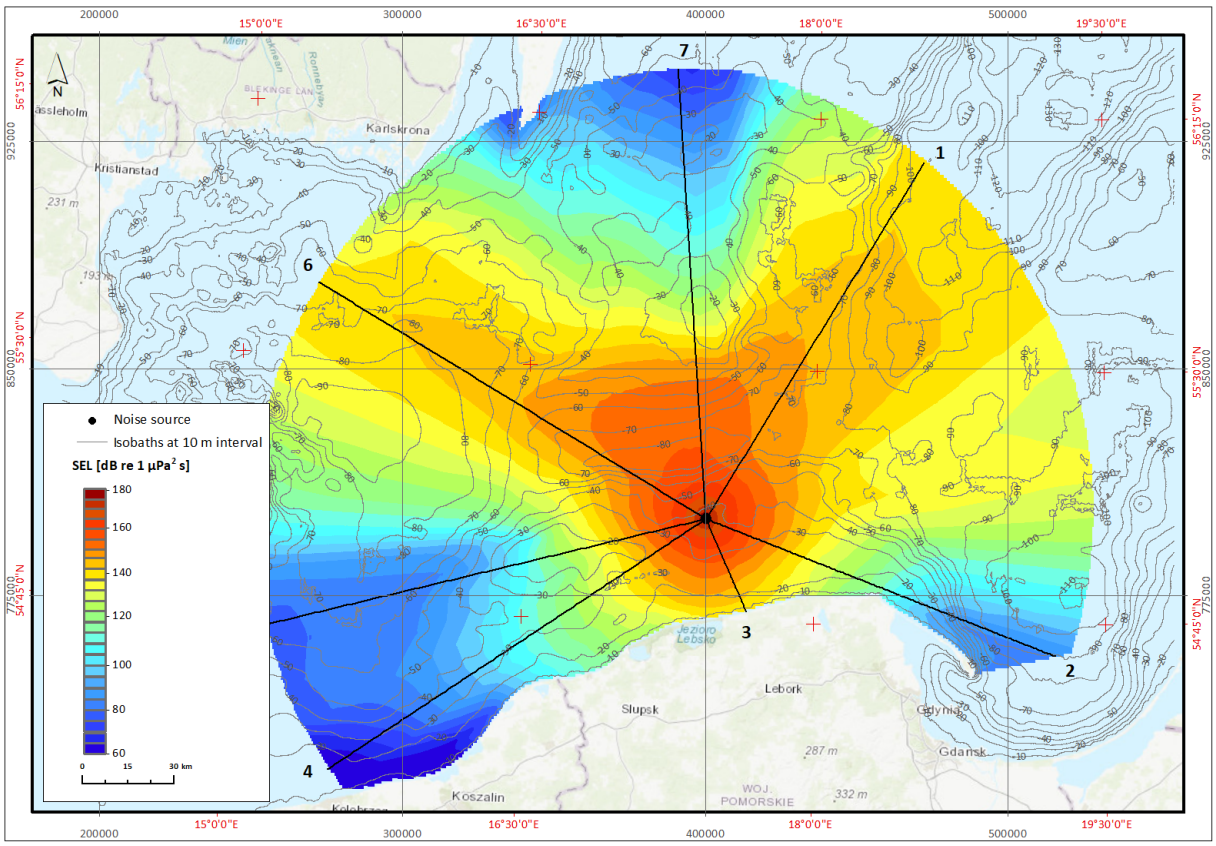

Figure 28. The acoustic map of the noise exposure level SEL (dB re 1 µPa^{2}s) caused by a single strike of a pile driver in the Baltica 3 Area

The lines present the described transects
Source: internal data

Similarly, as for the Baltica 2 Area, the sound propagation model for the Baltica 3 Area indicates two main directions (channels) of the sound spreading – north-eastern (transect 1) and north-western (transect 6), where similar sound levels values have been observed. Between the two channels in the northern direction (transect 7) and towards the coast line in the south transects 2, 4, and 5) the shallowing of the sea area exacerbates the sound propagation conditions and makes the SEL level decrease significantly. In the southern direction the Polish coast is located in at distance shorter than 40 km from the sound source and is subject to the impact of the sound wave with the exposure level SEL around 135 dB (transect 3) which is 15 dB higher in comparison to the level observed in the Baltica 2 Area.

The sound propagation along the transect 1 (Figure 29) is almost unimpeded, from the source located at the depth of 20 m in the direction of an axis of the underwater sound channel located at the depth of around 45 m. At longer distances (>30 km) from the source, the low vertical structure of the sound propagation is notable.

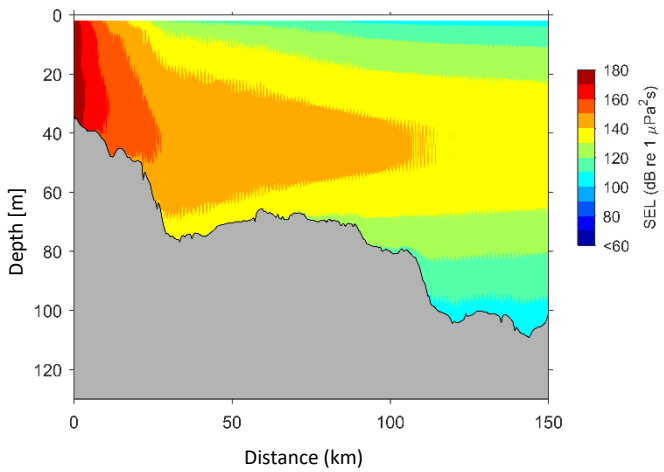

Figure 29. The model of the sound propagation along transect 1 – the sound exposure level SEL (dB re 1 μPa²·s) for a single strike of a pile driver

Source: internal data

In contract to the considered above situation regarding transect 1, the sound, spreading along transect 2 (Figure 30) encounters shallows in the coastal area. The transmission losses are substantial. After crossing the threshold located within 80 km from the source, the remaining sound energy spreads in a deep pool in which the sound propagation takes place in an unimpeded environment and the low frequency vertical structure of the sound field becomes clearly notable.

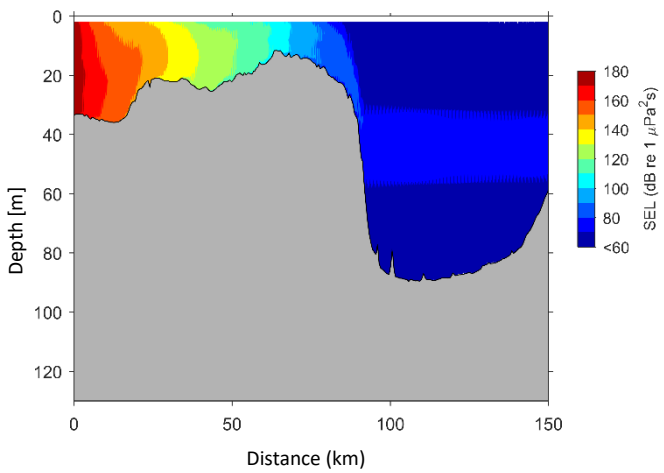

Figure 30. The model of the sound propagation along transect 2 – the sound exposure level SEL (dB re 1 μPa²·s) for a single strike of a pile driver

Source: internal data

The shortest section between the sound propagation source and the coast is located along transect 3 (Figure 31). The sound propagation is supported by a gently sloping shelf which does not rise significantly up to the very coast. The SEL of a single strike of a pile driver on the coast slightly exceeds 135 dB and is higher from the values determined for the Baltica 2 Area.

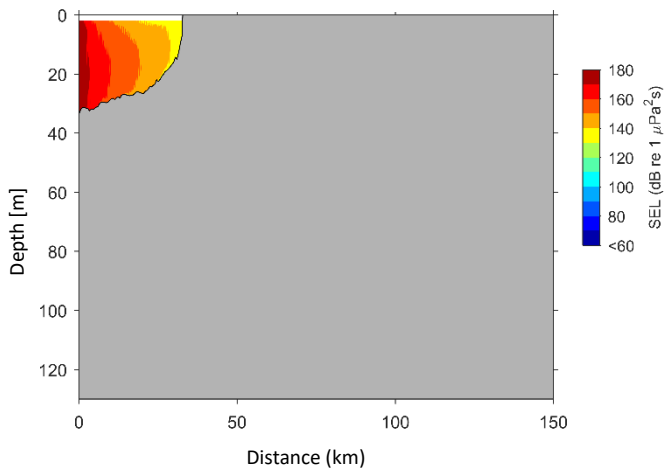

Figure 31. The model of the sound propagation along transect 3 – the sound exposure level SEL (dB re 1 μPa²·s) for a single strike of a pile driver

Source: internal data

The sound spreading in parallel to the coast in the case of transect 4 (Figure 32) again shows the increased transect loss resulting from the depth. The depth of water is smaller than the centre of the sound channel, so the sound is bent towards the seabed where a part of the energy is absorbed by the substrate and the attenuation phenomenon occurs.

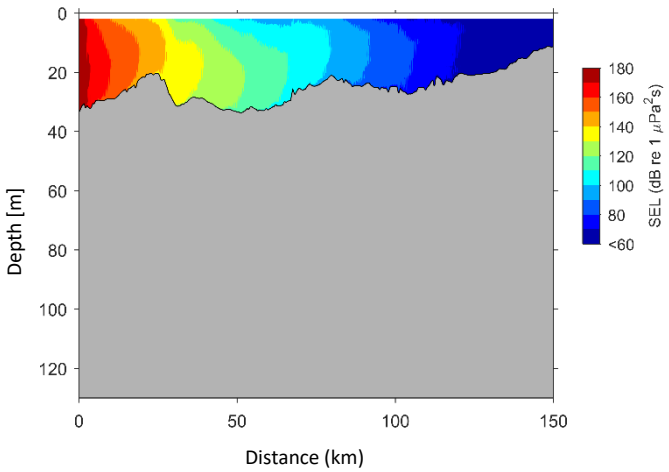

Figure 32. The model of the sound propagation along transect 4 – the sound exposure level SEL (dB re 1 μPa²·s) for a single strike of a pile driver

Source: internal data

The sound propagation along transect 5 (Figure 33) is similar to the one presented along transect 2 (Figure 30). Due to the shallow water areas at the distance of around 70 km from the sound source, the transmission loss SEL expressed with gradient is large and reaches the maximum at the threshold. A shallow water column above the threshold acts as a new but weak sound propagation source in the area at the distance of over 80 km from the primary source. The sound propagates

along the seabed until it reaches the sound channel where it propagates further at the lower vertical structure.

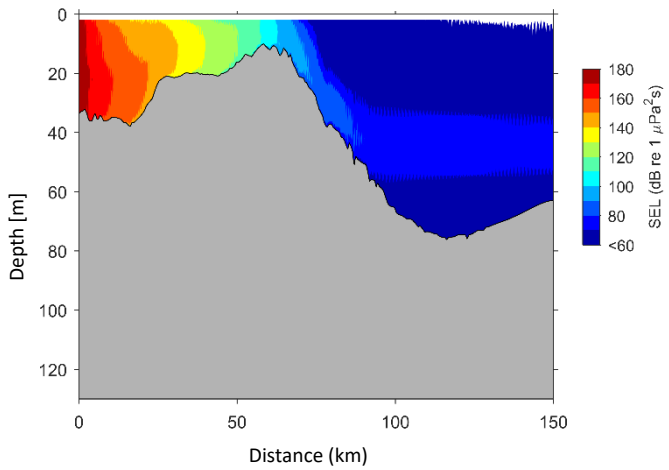

Figure 33. The model of the sound propagation along transect 5 – the sound exposure level SEL (dB re 1 μPa²·s) for a single strike of a pile driver

Source: internal data

Transect 6 (Figure 34) is similar to transect 2 (Figure 30) but propagation of the sound which reaches the sound channel is impeded by two shallow water areas within 20 and 70 km from the source. The sound propagates at the maximum SEL in the centre of the sound channel.

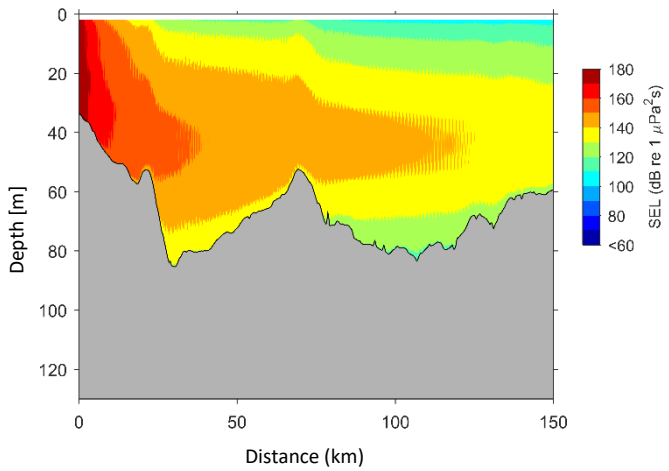

Figure 34. The model of the sound propagation along transect 6 – the sound exposure level SEL (dB re 1 μPa²·s) for a single strike of a pile driver

Source: internal data

Transect 7 (Figure 35) shows the sound propagation in the northern direction where the main sound propagation path is directed downwards, towards the valley until it reaches the sound channel. The main propagation path runs according to the depth in the shallow water area at the distance of around 60 km and then downwards to the next valley and to the next shallow waters areas. Large gradient in the SEL in the shallow waters area indicates a great transmission loss due to the depth.

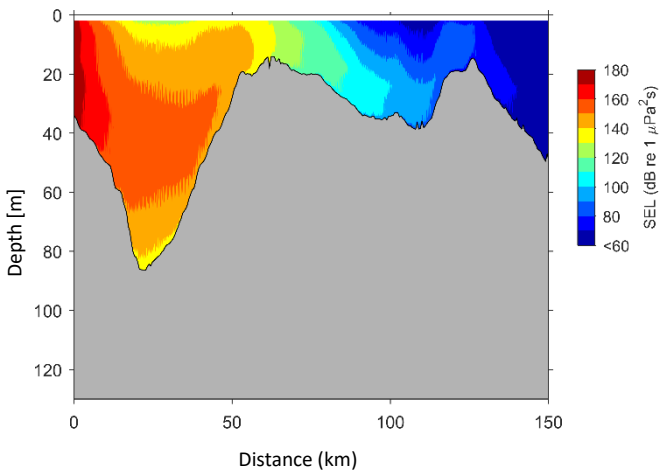

Figure 35. The model of the sound propagation along transect 7 – the sound exposure level SEL (dB re 1 μPa²·s) for a single strike of a pile driver

Source: internal data

The direct comparison of the curves reflecting the maximum SEL values along all 7 transects designated on the acoustic map illustrates the impact of the depth on the logarithmic form of the transmission loss (Figure 36).

Transects 1 and 6 are close to the logarithmic form of the transmission loss but the increased transmission losses occurred on the first kilometres from the source. The SEL drops caused by the occurrence of the shallow waters areas are notable in the sound channel in the case of the transect 6. In the case of transect 7, the sound may spread well through the first 40 km but further away a great transmission loss occurs. In the case of other transects, the sound travels through the mass transmission loss starting from the very beginning; at transects 2 and 5 the logarithmic transmission loss has been demonstrated at the distance of over 90 km from the source.

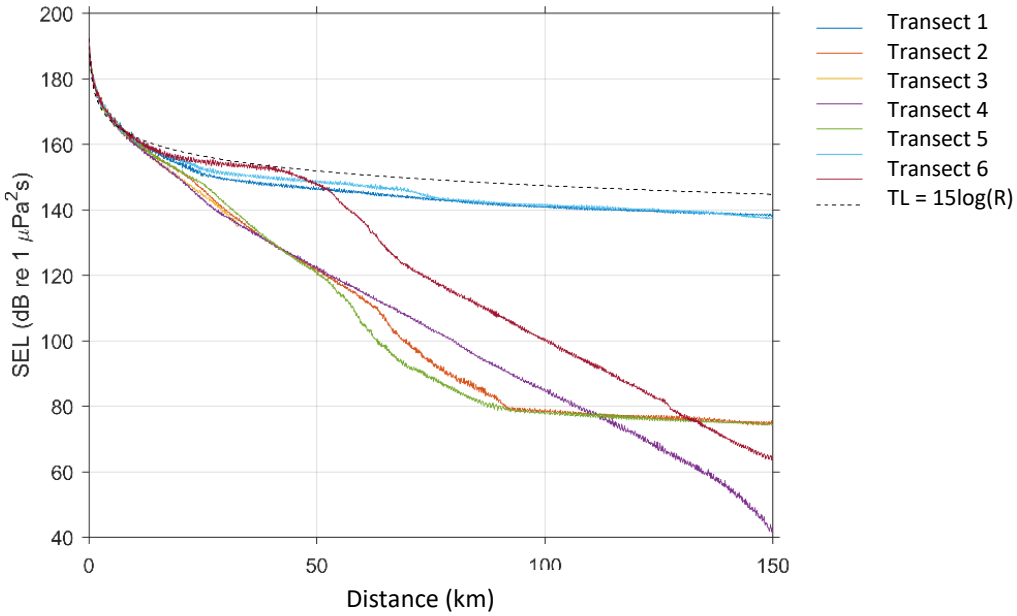

Figure 36. The summary of the maximum SELs during a single strike with a pile driver along designated transects

Source: internal data

4.3.2 Impact range

4.3.2.1 Grey and harbour seals

The average impact range for behavioural reaction equals 4.1 km (Figure 37, green line), and the maximum – 4.6 km. The impact ranges for the TTD and the PTS based on the noise exposure level for a single strike of a pile driver in all directions are shorter than 0.1 km (Figure 37, red line localised within the sound source). In the case of the SEL for cumulative strikes (1 hour) the average impact range for the TSS equals 6.1 km and the maximum is 7.1 km (Figure 37, orange line). However, the average impact range for the PTS equals 0.8 km and the maximum is 1.1 km (Figure 37, red line localised within the sound source).

For the SPL_{peak} (Figure 38) the impact ranges are shorter than 0.1 km.

A summary of the impact ranges from the source have been presented in the table below (Table 9).

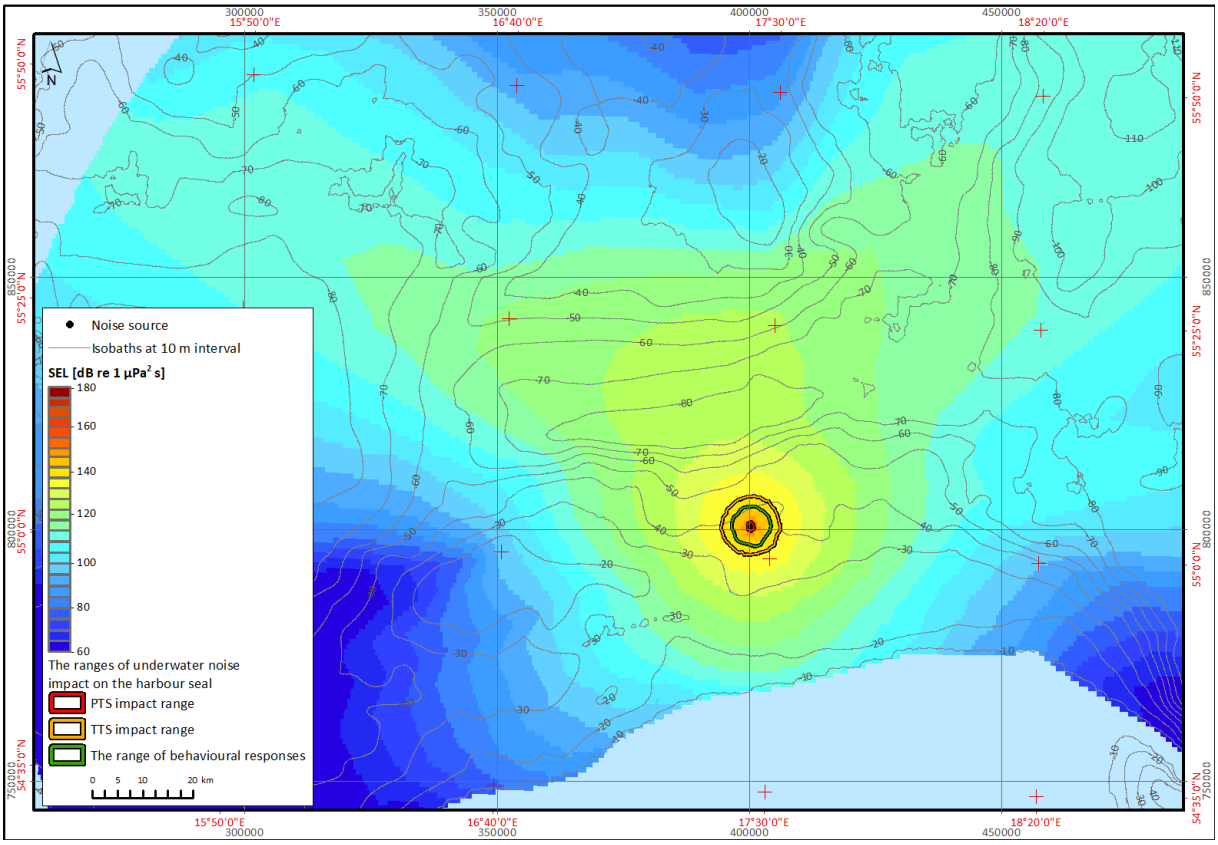

Figure 37. The acoustic map of the weighted (PW) noise exposure level SEL (dB re 1 µPa^{2}s) caused by a single strike of a pile driver in the Baltica 3 Area

The ranges of TTS and PTS impacts based on SEL_{cum}

Source: internal data

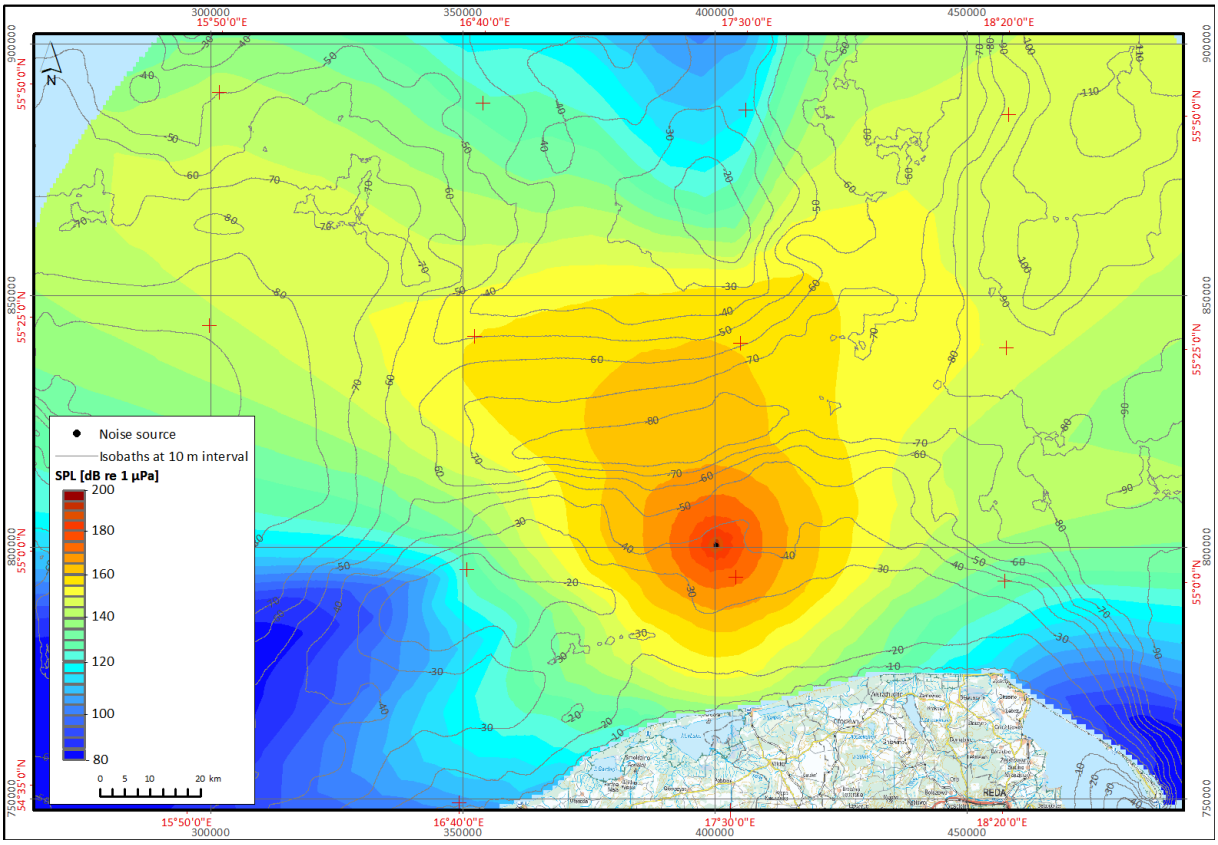

Figure 38. Acoustic map of the sound pressure level SPL_{peak} taking into account the threshold values in the Baltica 3 Area

The PTS and the TTS impact ranges as well as the behavioural reaction range (<0.1 km) have been depicted with the use of the black spot in the noise source location
Source: internal data

Table 9. The impact ranges in the case of grey and harbour seals

Threshold value	SEL [dB re 1 µPa²s]	Average distance [km]	Maximum distance [km]	SPL_{peak} (dB re 1 µPa)	Average distance [km]	Maximum distance [km]
Behavioural reaction	158	4.1	4.6	212	0.1	0.1
TTS (a single pile driver strike)	170	0.1	0.1	212	0.1	0.1
TTS (cumulated impact [1 hour])	170	6.1	7.1	--	--	--
PTS (a single pile driver strike)	185	0.1	0.1	218	0.1	0.1
PTS (cumulated impact [1 hour])	185	0.8	1.1	--	--	--

The PW weight has been applied in the case of the SEL for the TTS and the PTS values. The weight has not been applied in the case of the SPL_{peak} and behavioural reactions
Source: internal data

4.3.2.2 Porpoises

Due to the lower threshold values for porpoises in comparison to seals, the impact ranges (Figure 39, Figure 40) are wider. The average range of behavioural reactions equals 24.1 km and the maximum

42.4 km. The average impact range for the TTS equals 1.2 km for the SEL caused by a single strike with a pile driver and 19.1 km for a cumulative sound exposure level, and the maximum range equals 1.9 km and 27.2 km respectively (Figure 39, orange line). The impact ranges for the PTS are smaller than for the TTS and show an almost round shape around the source with the maximum radius not exceeding 0.1 km for the SEL triggered by a single strike and 9.1 km for the SEL_{cum} (Figure 39, red line). The average impact ranges for the PTS in all directions amount to: 0.1 km for the single and 7.8 km for the cumulative SEL.

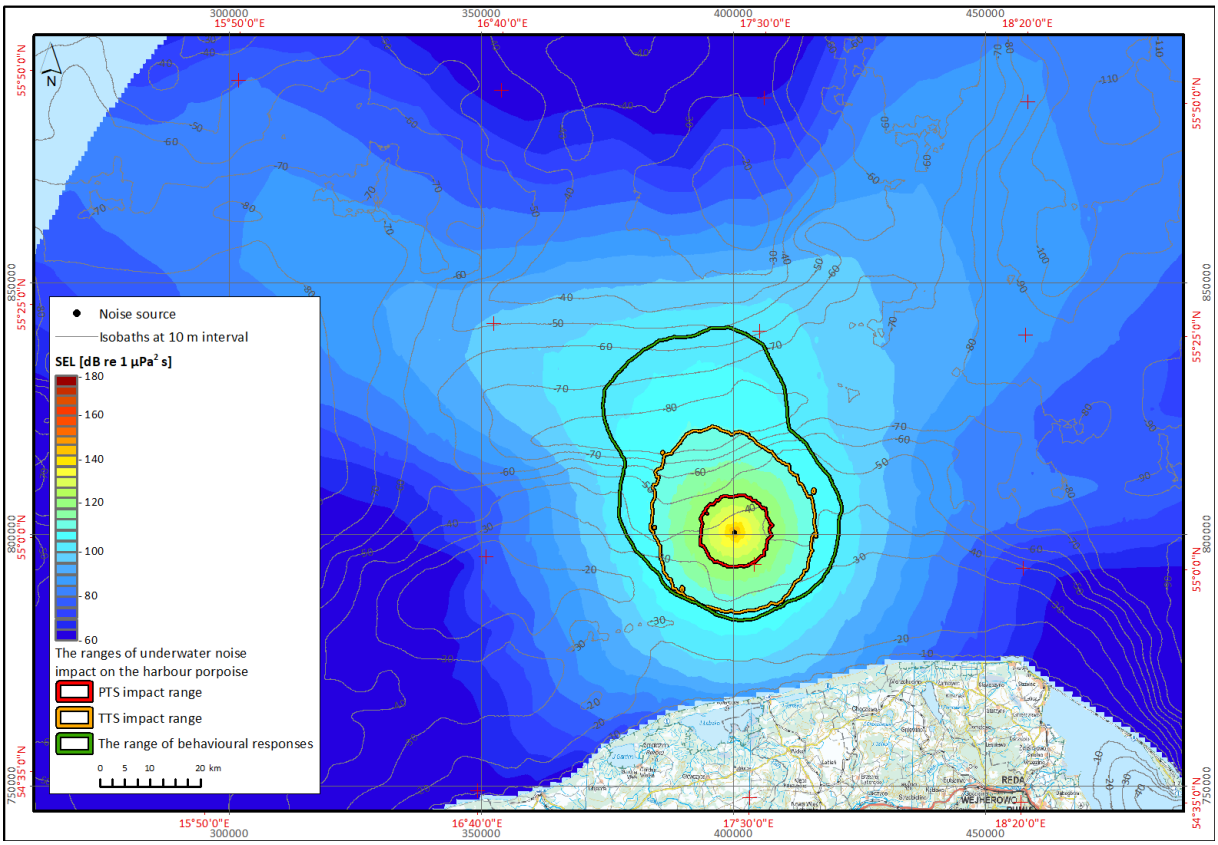

Figure 39. The acoustic map of the weighted (HF) noise exposure level SEL (dB re 1 µPa²s) caused by a single strike of a pile driver in the Baltica 3 Area

The ranges of TTS and PTS impacts based on SEL_{cum}
Source: internal data

The ranges SPL_{peak} (Figure 40) are available only for the TTS and PTS and are below the impact ranges based on the SEL. The impact ranges for the TTS and for the PTS are both circular in shape and have a constant radius of 0.3 and 0.1 km respectively.

A summary of the impact ranges from the source have been presented in the table below (Table 10).

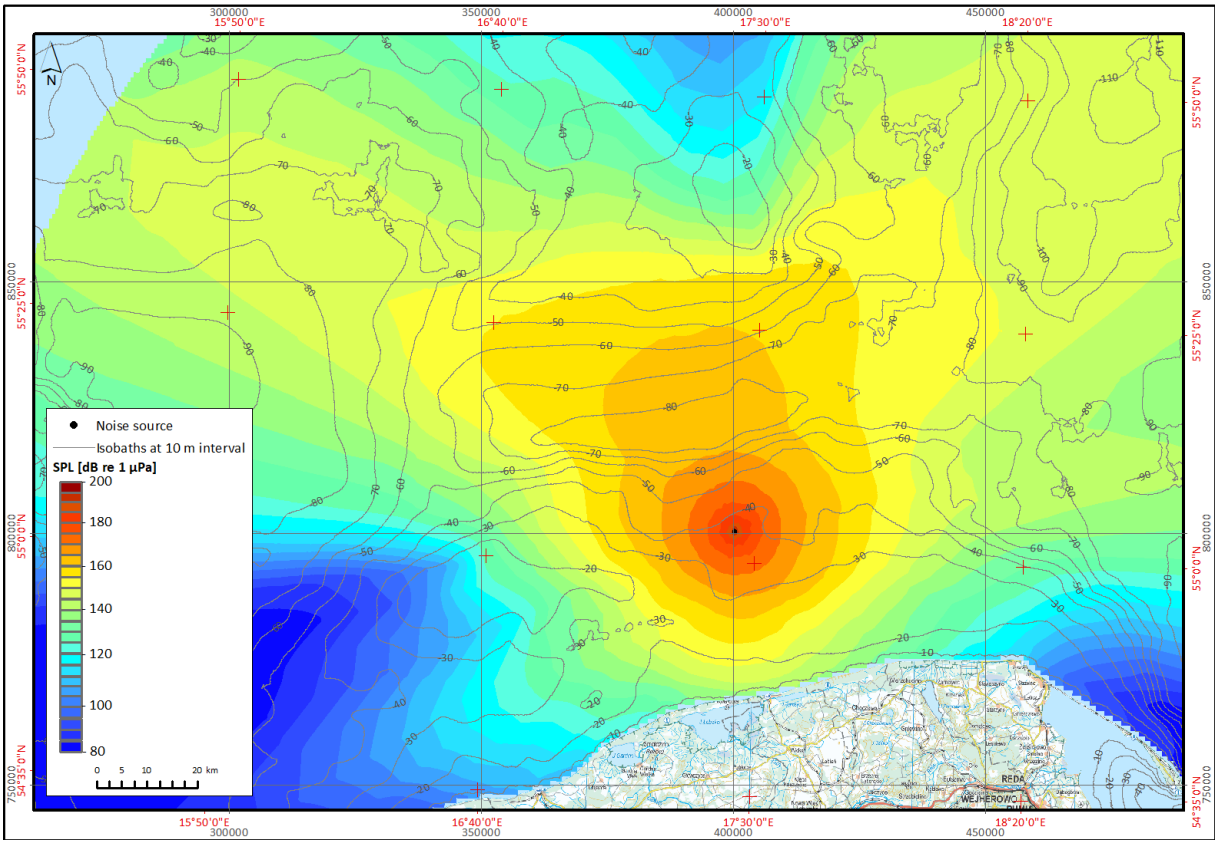

Figure 40. Acoustic map of the sound pressure level SPL_{peak} taking into account the threshold values in the Baltica 3 Area

The PTS and the TTS impact ranges as well as the behavioural reaction range (<0.1 km) has been depicted with the use of the black spot in the noise source location
Source: internal data

Table 10. The impact ranges in the case of porpoises

Threshold value	SEL [dB re 1 µPa²s]	Average distance [km]	Maximum distance [km]	SPL_{peak} (dB re 1 µPa)	Average distance [km]	Maximum distance [km]
Behavioural reaction	140	24.1	42.4	--	--	--
TTS (a single pile driver strike)	140	1.2	1.9	196	0.3	0.3
TTS (cumulated impact [1 hour])	140	19.1	27.2	--	--	--
PTS (a single pile driver strike)	155	0.1	0.1	202	0.1	0.1
PTS (cumulated impact [1 hour])	155	7.8	9.1	--	--	--

The HF weight has been applied in the case of the SEL for the TTS and PTS values. The weight has not been applied in the case of the SPL_{peak} and behavioural reactions
Source: internal data

4.3.2.3 Ichthyofauna

The impact ranges for the TTS and the PTS for fish with and without the swim bladder are calculated on the basis of the noise exposure level triggered by a single strike with a pile driver (within 1 hour).

The level of multiple strikes of a pile driver is higher than a single strike by 34.5 dB. The difference between the threshold values for the TTS and the PTS equals 30 dB for fish without the swim bladder and 17 dB for fish with the swim bladder. Due to the similarity of differences between the SEL and SEL_{cum} from one hand and between the thresholds for the TTS and the PTS from the other, the impact range for the TTS based on the SEL is similar to the impact range for the PTS based on the SEL_{cum}.

The impact ranges for fish without the swim bladder have been provided in the table (Table 11) and the modelling results have been demonstrated in the diagram below (Figure 41).

Table 11. The impact ranges in the case of fish without the swim bladder

Threshold value	SEL [dB re 1 µPa²s]	Average distance [km]	Maximum distance [km]
Behavioural reaction	142	19.9	31.8
TTS (a single pile driver strike)	186	0.1	0.1
TTS (cumulated impact [1 hour])	186	9.1	9.1
PTS (a single pile driver strike)	216	0.1	0.1
PTS (cumulated impact [1 hour])	216	0.1	0.1

The threshold value applies to the sound exposure level without taking into account the weight
Source: internal data

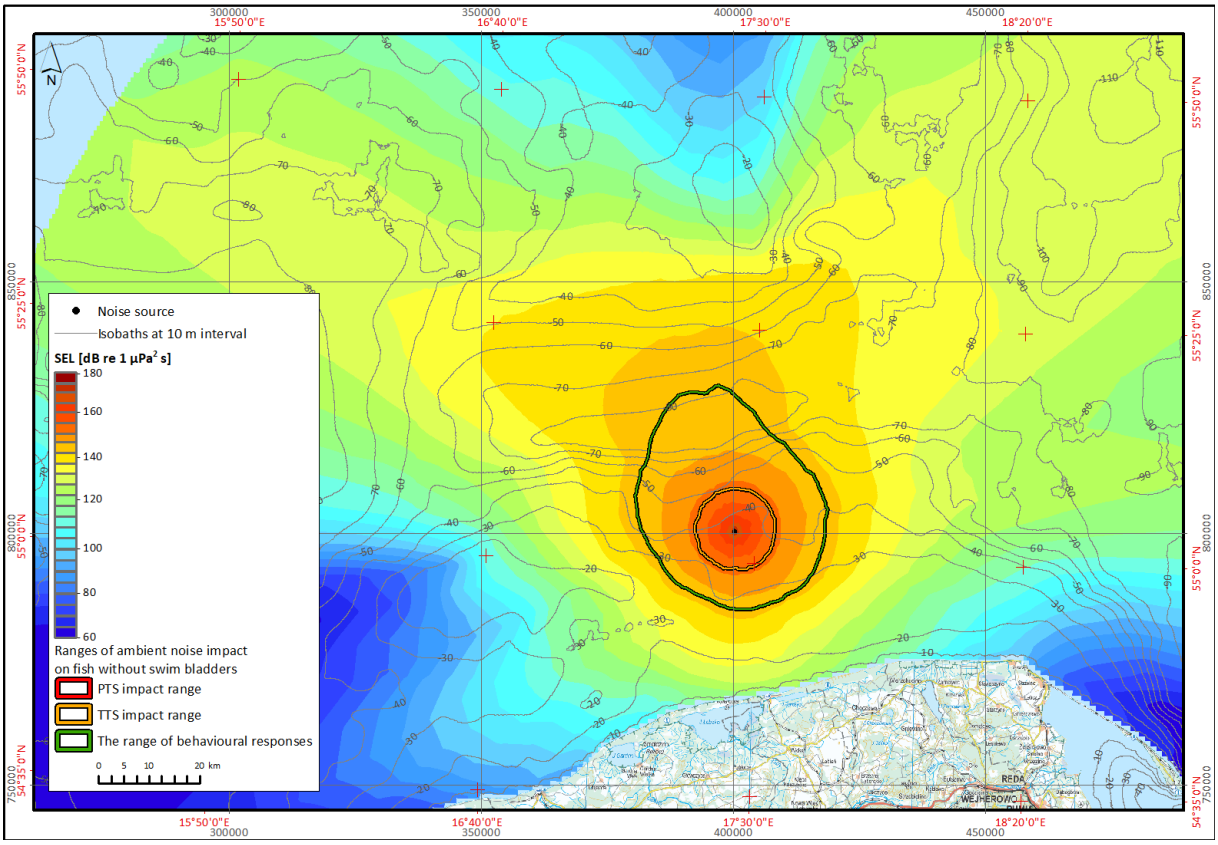

Figure 41. The acoustic map of the noise exposure level SEL (dB re 1 µPa²s) caused by a single strike of a pile driver in the Baltica 3 Area in the case of fish without the swim bladder

The ranges of TTS and PTS impacts based on SEL_{cum}
Source: internal data

The impact ranges for fish with the swim bladder have been provided in the table (Table 12) and the modelling results have been demonstrated in the diagram below (Figure 42).

Table 12. The impact ranges in the case of fish with the swim bladder

Threshold value	SEL [dB re 1 µPa²s]	Average distance [km]	Maximum distance [km]
Behavioural reaction	135	33.5	64.3
TTS (a single pile driver strike)	186	0.1	0.1
TTS (cumulated impact [1 hour])	186	8.2	9.1
PTS (a single pile driver strike)	203	0.1	0.1
PTS (cumulated impact [1 hour])	203	1.0	1.3

The threshold value applies to the sound exposure level without taking into account the weight
Source: internal data

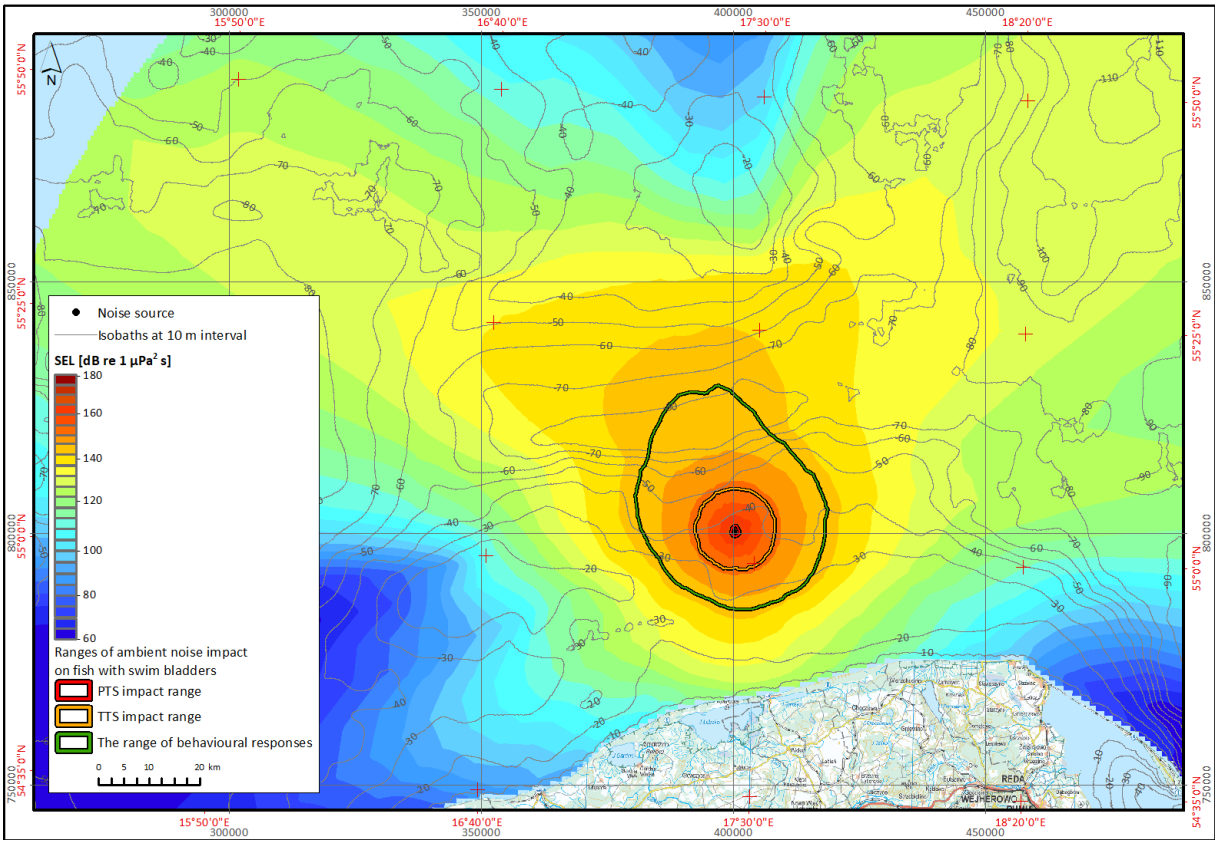

Figure 42. The acoustic map of the noise exposure level SEL (dB re 1 µPa²s) caused by a single strike of a pile driver in the Baltica 3 Area in the case of fish with the swim bladder

The ranges of TTS and PTS impacts based on SEL_{cum}
Source: internal data

5 Modelling of noise propagation as a result of single location piling

The cumulative noise impact range has been determined on the basis of the modelling of the noise propagation as a result of a multiple location piling taking into account the noise mitigation system in the form of a bubble curtain. All calculations of the noise propagation demonstrated in this section take into account the use of the noise mitigation system.

5.1 Methods

In the explored area there is a possibility of accumulation of the noise created as a result of piling which results from carrying out simultaneous pilings in two or more locations. Therefore, there is a possibility of the increase of the OWF's impact range on marine mammals and fish through overlapping acoustic fields from the specific sources.

Based on numerical simulations the conservative calculations of the impact areas which are dependent on the number of places where the piling is simultaneously carried out have been determined (it will not be dependent on the distance between the locations and their distribution as it constitutes the superposition of the impact areas with the assumption that the impact areas from single pilings do not overlap). Therefore, it was possible to run various combinations taking into account simultaneous piling in 4 locations in the Baltica OWF, the BŚII OWF, and the BŚIII OWF.

The impact assessment criteria (behavioural reaction, temporary hearing threshold shift TTS or permanent hearing loss PTS) and the impact assessment itself are the same as in the case of a single noise source.

Assuming that the noise characteristics for all sources are similar, the main task is to identify to what extent the noise from specific locations will be overlapping (adding up). Three various approaches different from each other in terms of the distance between the subsequent noise sources have been applied.

5.1.1 Superimposition of the noise from sources located near each other (<1 km)

The sources located near each other are treated as two sources in the same location. The spectra of both noise sources must be superimposed in order to be able to receive the cumulative spectrum to which the acoustic waves attenuation level can be then referred (TL). The cumulative sound exposure level $\mathrm{SEL_{cum}}$ is determined on the basis of the separate sound exposure levels for specific sources:

$$\mathrm{SEL_{cum}} = \mathrm{SEL} + 10\ \log_{10} n$$

Assuming that the spectrum for specific sources is equal and the number of sources is equal n – for the neighbouring sources $\mathrm{SEL_{cum}} = \mathrm{SEL} + 3$ dB. Therefore, the noise will increase by 3 dB.

5.1.2 Superimposition of the noise from sources at a medium distance from each other (20 km)

Superimposition of the acoustic fields for sources at the distance of 20 km from each other has been calculated for points located in the western location (55,0669°N; 17,1034°E) and in the eastern location (55,0561°N; 17,4377°E).

The noise levels from the eastern location have been interpolated on the western area grid. The noise levels from every subsequent pixel (cell) of the grid are added to each other (square amplitude values). The conversion of the noise level to decibels is carried out according to the following equation:

$$\mathrm{SEL_{cum}} = 10\ \log_{10}\left(\sum_i 10^{0.1\ \mathrm{SEL}_i}\right)$$

where:

SEL_i means noise exposure determined for a cell of the grids for which calculations are being made.

Due to various distances from the noise source, various sea-bed topography and various TL parameters, the values SEL_i differ for specific sources, thus a simple summation presented in 5.1.1 cannot be performed.

5.1.3 Superimposition of the noise from sources located far each other (<1 km)

If piling is carried out in locations sufficiently distant from each other so that their impact areas do not overlap, the threshold values and the impact areas are summed up. The noise level increase (by the noise from a significantly distant source) is considered negligible. It needs to be noted that for shorter distances of the threshold values for impacts (e.g. the PTS) this assumption is correct also for the distances shorter than 20 km. In this case the assumption regarding the negligible noise increase can be met if the distance is a minimum double threshold value of the distance determined for a single noise level.

5.2 Results

The superimposition of the acoustic fields in all mentioned scenarios designates various impact areas dependent on the spatial distribution of the sites. In order to prepare all possible spatial combinations (distances between sources), the results from each combination have been increased by an appropriate precaution/safety index:

- marine mammals (porpoises, grey and harbour seals) – index 1.2;
- fish – index 1.5.

5.2.1 Grey and harbour seals

The ranges of impact on seals increase along with the number of the locations where piling takes place. This is presented on the maps for one location (Figure 22, Figure 37), for two locations close to each other (Figure 43), for two locations at the distance of 20 km from each other (Figure 44), for three locations (Figure 45) in the table (Table 13).

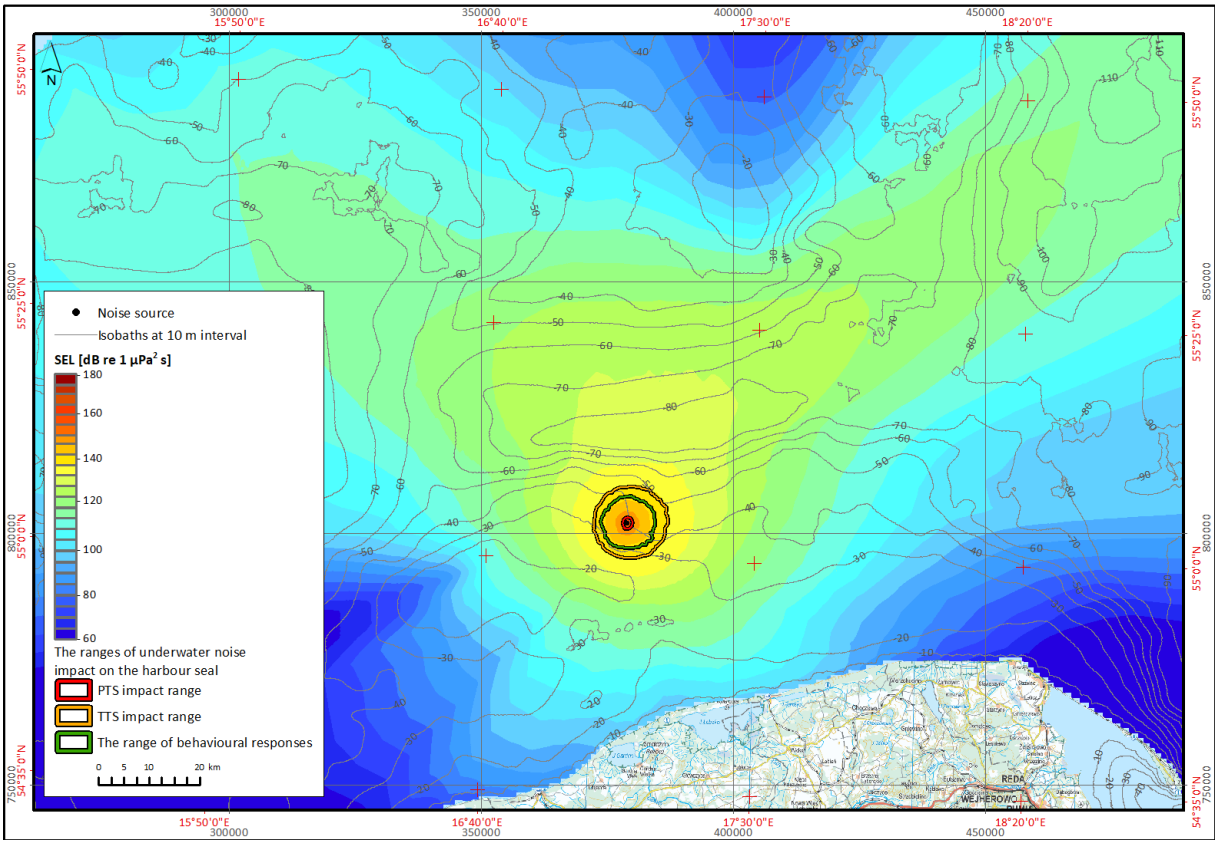

Figure 43. The acoustic map of the weighted (PW) noise exposure level SEL (dB re 1 µPa²s) triggered by a single strike of a pile driver in two locations close to each other

The ranges of TTS and PTS impacts based on SEL_{cum}

Source: internal data

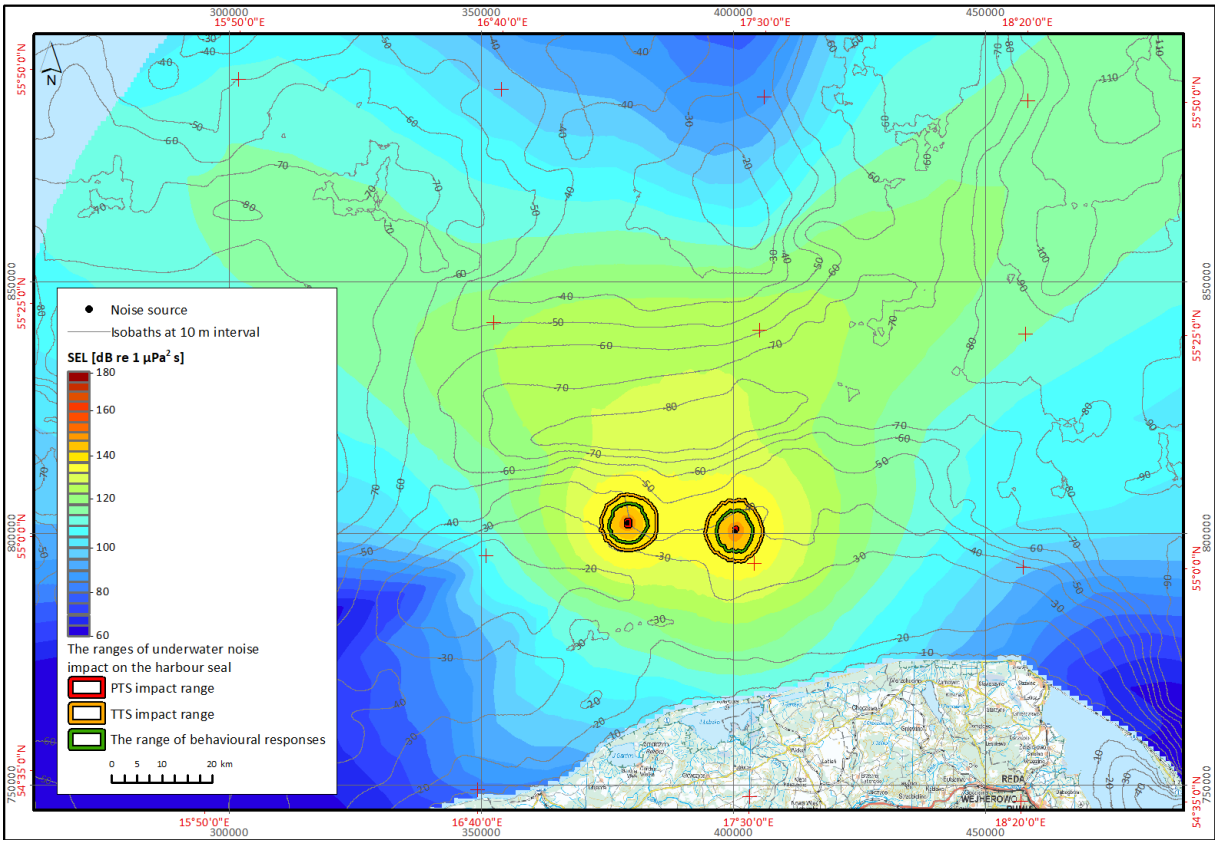

Figure 44. The acoustic map of the weighted (PW) noise exposure level SEL (dB re 1 µPa^{2}s) triggered by a single strike of a pile driver in two locations at the distance of 20 km from each other

The ranges of TTS and PTS impacts based on SEL_{cum}

Source: internal data

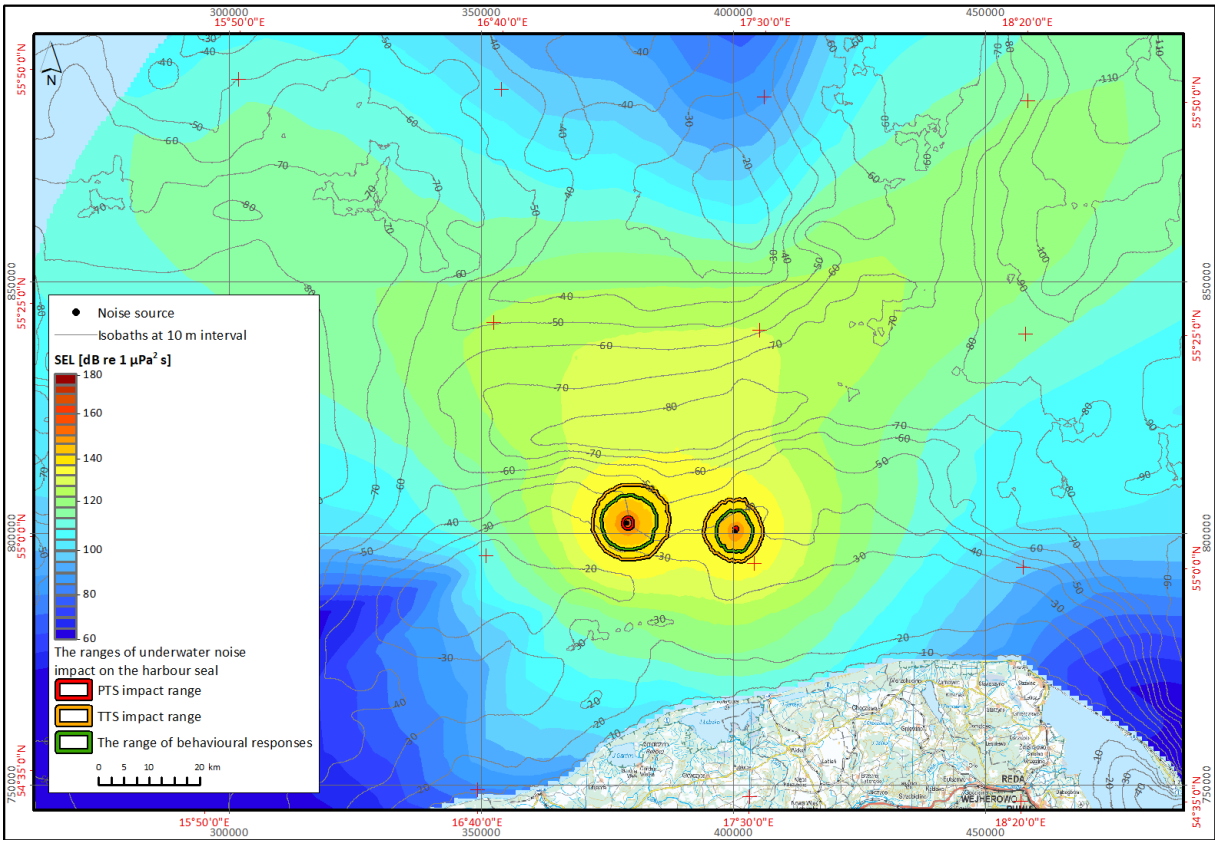

Figure 45. The acoustic map of the weighted (PW) noise exposure level SEL (dB re 1 µPa^{2}s) caused by a single strike of a pile driver in three locations (two neighbouring and one 20 km away).

The ranges of TTS and PTS impacts based on SEL_{cum}

Source: internal data

Table 13. The impact ranges [km] for seals for the noise from sources 1, 2 and 3

SEL threshold value (dB re 1 µPa²s)		1 source	2 sources (2 neighbouring sources)	2 sources (2 sources at the distance of 20 km)	2 sources (2 sources at a significant distance)	3 sources (2 neighbouring sources/ 1 source at the distance of 20 km)	3 sources (2 at the distance of 20 km/ 1 source at a significant distance)
the average distance [km]	Behavioural reaction	4.0	5.6	8.0	8.0	9.6	12.0
	TTS (a single pile driver strike)	0.1	0.1	0.2	0.2	0.2	0.3
	TTS (cumulated impact [1 hour])	5.6	7.6	11.2	11.2	13.2	16.8
	PTS (a single pile driver strike)	0.1	0.1	0.2	0.2	0.2	0.3
	PTS (cumulated impact [1 hour])	0.7	1.1	1.4	1.4	1.8	2.1
um dist anc	Behavioural reaction	4.5	6.7	9.0	9.0	11.2	13.5

SEL threshold value (dB re 1 µPa²s)		1 source	2 sources (2 neighbouring sources)	2 sources (2 sources at the distance of 20 km)	2 sources (2 sources at a significant distance)	3 sources (2 neighbouring sources/ 1 source at the distance of 20 km)	3 sources (2 at the distance of 20 km/ 1 source at a significant distance)
	TTS (a single pile driver strike)	0.1	0.1	0.2	0.2	0.2	0.3
	TTS (cumulated impact [1 hour])	6.7	9.3	13.4	13.4	16	20.1
	PTS (a single pile driver strike)	0.1	0.1	0.2	0.2	0.2	0.3
	PTS (cumulated impact [1 hour])	0.8	1.4	1.6	1.6	2.2	2.4
the surface area of the impact [km²]	Behavioural reaction	49.3	97.6	98.6	98.6	147	148
	TTS (a single pile driver strike)	0.03	0.03	0.06	0.06	0.06	0.09
	TTS (cumulated impact [1 hour])	99.5	184	199	199	284	299
	PTS (a single pile driver strike)	0.03	0.03	0.06	0.06	0.06	0.09
	PTS (cumulated impact [1 hour])	1.7	4.1	3.4	3.4	5.8	5.1

The threshold values apply to the sound exposure level taking into account the weight. The threshold for a behavioural reaction is an exception and applies to the sound exposure level without taking into account the weight
In the simulations, the distance between the sources was established at 0 km in the case of neighbouring locations; for those located at the distance of 20 km it has been simulated that the acoustic fields overlap; and in the case of locations separated by significant distances the acoustic fields do not overlap and are aggregated
**Calculated based on the range of the variants accounting for 1 source and 2 sources at the distance of 20 km*
Source: internal data

Table 14. Conservative estimates of the area of impact [km²] on seals generated by noise from 1, 2, 3 and 4 pile driving locations in the worst case (sources separated by a significant distance)

Threshold value		1 source	2 sources	3 sources	4 sources
impact area [km²]	Behavioural reaction	49.3	120	178	237
	TTS (a single pile driver strike)	0.03	0.1	0.1	0.2
	TTS (cumulated impact [1 hour])	99.5	240	360	480
	PTS (a single pile driver strike)	0.03	0.1	0.1	0.2
	PTS (cumulated impact [1 hour])	1.7	4.1	6.1	8.2

The calculated impact areas are the sums of single impact areas increased by 20% (safety index 1.2)
Source: internal data

5.2.2 Porpoises

The impact ranges calculated for all the analysed impacts (behavioural reaction, TTS, PTS) increase with the growing number of pile driving locations It is presented in the maps drawn for a single location (Figure 24, Figure 39), two neighbouring locations (Figure 46), two locations separated by 20 km (Figure 47), three locations (Figure 48) and in the table (Table 15).

In the scenario allowing for two sources of noise, radius and the area of almost all kinds of impact were the smallest when pile driving operations were conducted simultaneously in two neighbouring locations (Figure 46). They were greater for pile driving conducted at the distance of 20 km (Figure 47) and the greatest for pile driving located within the distance which makes it impossible for the acoustic fields to overlap (Table 15).

The PTS impact determined based on the cumulated level of exposition to noise is an exception from the rule. The distance of 20 km is significant enough to prevent overlapping of impact areas (Figure 47). Increase in SEL associated with another noise source makes the cumulated noise level exceed the threshold established for PTS. The range and area of the impact are greater than in the assumption of independent noise propagation from sources located at a significant distance from each other.

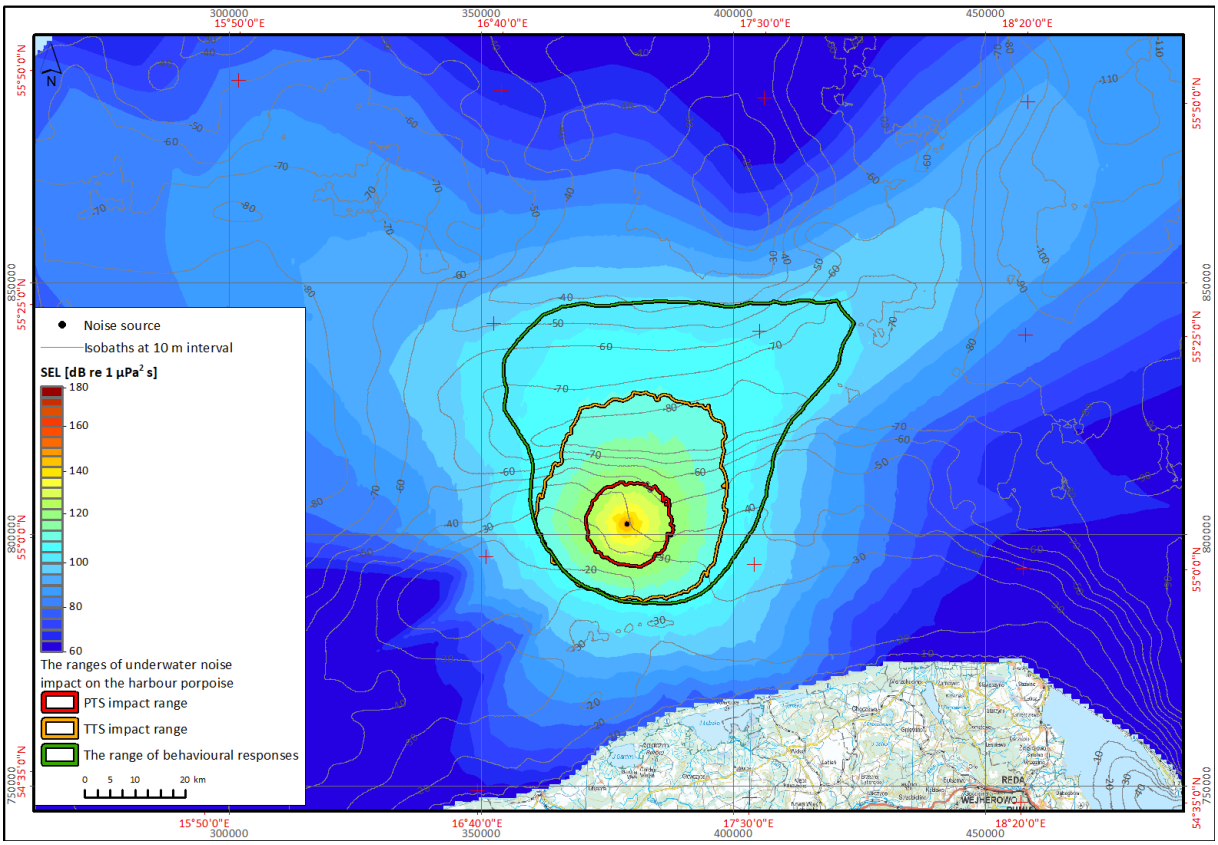

Figure 46. Acoustic map of HF-weighted SEL noise exposition level (dB re 1 µPa²s) generated by single strikes of pile drivers in two neighbouring locations within the Baltica OWF

The ranges of TTS and PTS impacts based on SEL_{cum}
Source: internal data

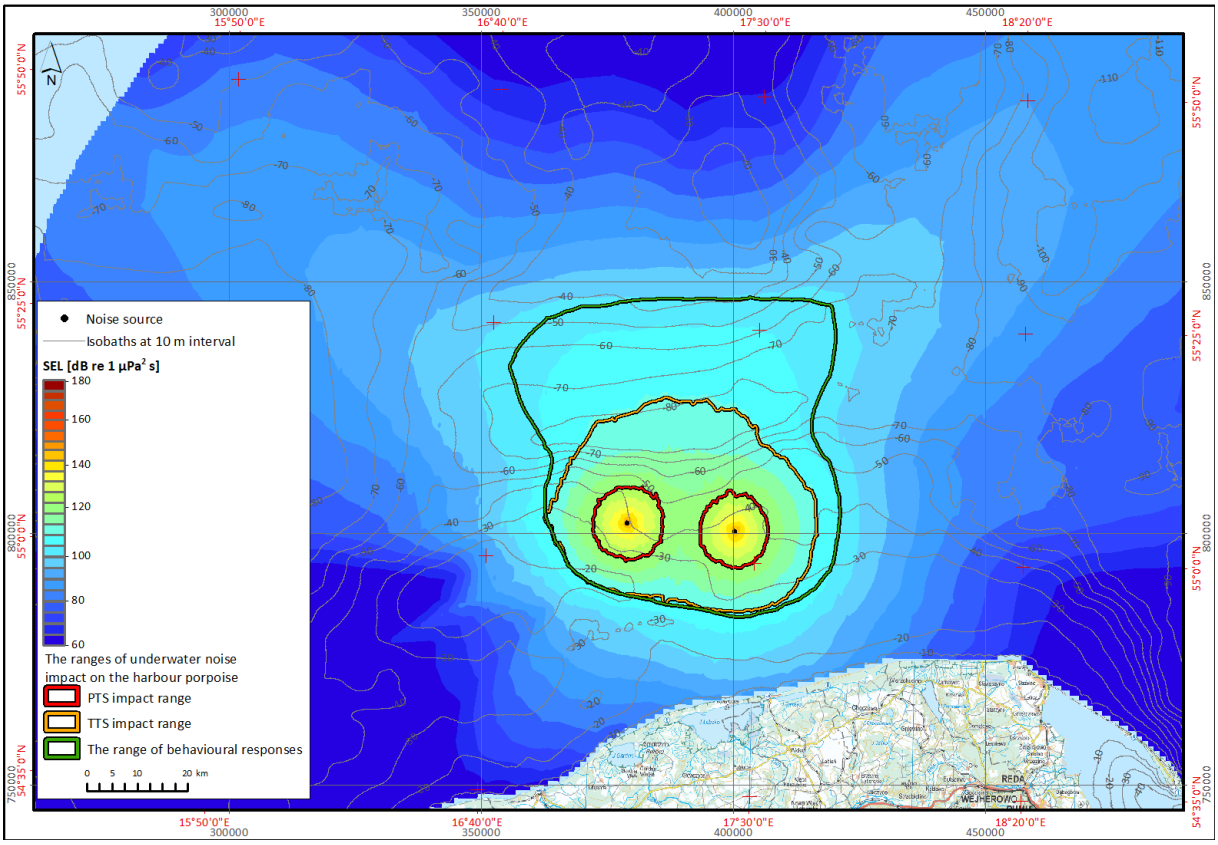

Figure 47. Acoustic map of HF-weighted SEL noise exposition level (dB re 1 µPa²s) generated by single strikes of pile drivers in two locations separated by 20 km

The ranges of TTS and PTS impacts based on SEL_{cum}
Source: internal data

In the case of simultaneous pile driving in three locations, there was numerically simulated a situation where two locations are near and the third one is at the distance of 20 km (Figure 48, Table 15).

The impact area is larger than in each studied scenario allowing for 2 locations of noise sources, though its radius will be smaller than in the case of 2 locations separated by a significant distance as the impacted space will be more compact. If two locations are at the distance of 20 km and the third one is located even further, the radius and space may be calculated just like in the case of two locations separated by 20 km (Figure 47) or a single source (Figure 24, Figure 39) by means of simple aggregation (Table 15). This option will involve much greater ranges of impact than two neighbouring locations and one location 20 km away.

The entire impact (excluding the PTS threshold value determined by the SEL_{cum}), radii and impacted areas are greater than in the case of locations separated by a significant distance.

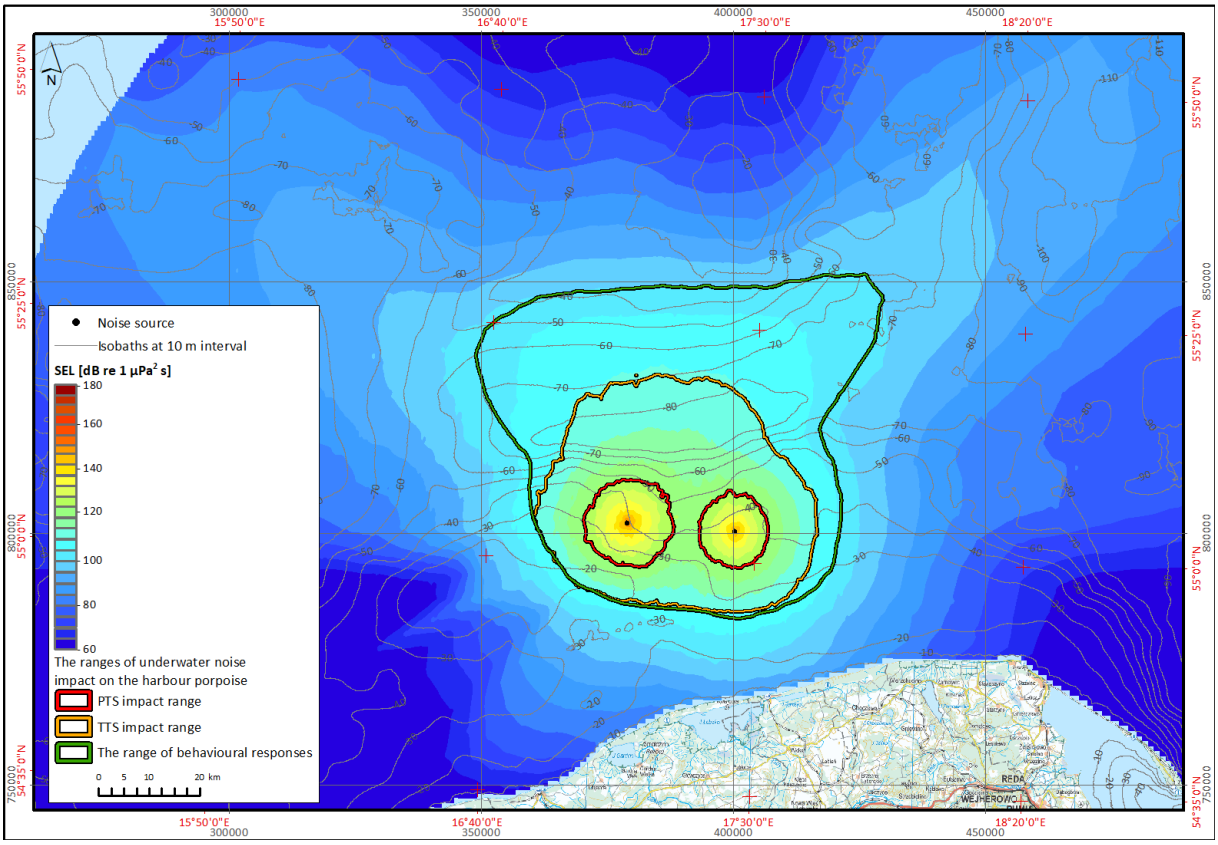

Figure 48. Acoustic map of HF-weighted SEL noise exposition level (dB re 1 µPa²s) generated by single strikes of pile drivers in three locations (two neighbouring and one at the distance of 20 km)

The ranges of TTS and PTS impacts based on SEL_{cum}

Source: internal data

Table 15. The area of impact [km] on harbour porpoises for noise from 1, 2 and 3 sources

SEL threshold value (dB re 1 µPa²s)		1 source	2 sources (2 neighbouring sources)	2 sources (2 sources at the distance of 20 km)	2 sources (2 sources at a significant distance)	3 sources (2 neighbouring sources/ 1 source at the distance of 20 km)	3 sources (2 at the distance of 20 km/ 1 source at a significant distance)
the average distance [km]	Behavioural reaction	22.8	28.2	29.7	**45.6**	32.9	**52.5**
	TTS (a single pile driver strike)	1.2	1.8	1.2	**2.4**	1.8	**2.4**
	TTS (cumulated impact [1 hour])	18.5	22.2	23.5	**37.0**	26.0	**42**
	PTS (a single pile driver strike)	0.1	0.2	0.1	0.2	0.2	**0.2**
	PTS (cumulated impact [1 hour])	7.9	9.5	10.2	**15.8**	11.6	**18.1**
the maximum distance [km]	Behavioural reaction	46.0	62.7	59.9	**92.0**	69.9	**106**
	TTS (a single pile driver strike)	1.8	2.5	1.8	**3.6**	2.5	**3.6**
	TTS (cumulated	26.3	37.0	38.5	**52.6**	42.1	**64.8**

SEL threshold value (dB re 1 µPa²s)		1 source	2 sources (2 neighbouring sources)	2 sources (2 sources at the distance of 20 km)	2 sources (2 sources at a significant distance)	3 sources (2 neighbouring sources/ 1 source at the distance of 20 km)	3 sources (2 at the distance of 20 km/ 1 source at a significant distance)
	impact [1 hour])						
	PTS (a single pile driver strike)	0.1	0.2	0.1	**0.2**	0.2	**0.2**
	PTS (cumulated impact [1 hour])	9.4	11.7	**28.7**	18.8	28.7	**38.1**
impact area [km²]	Behavioural reaction	1953	3104	3460	**3906**	4208	**5413**
	TTS (a single pile driver strike)	4.5	9.9	4.5	**9.0**	10.0	**9.0**
	TTS (cumulated impact [1 hour])	1114	1662	1966	**2228**	2369	**3080**
	PTS (a single pile driver strike)	0.03	0.1	0.03	**0.06**	0.1	**0.06**
	PTS (cumulated impact [1 hour])	197	284	**448**	394	524	**645**

The threshold values refer to the noise exposition levels with the weight taken into account
In the simulations, the distance between the sources was established at 0 km in the case of neighbouring locations; for those located at the distance of 20 km it is simulated that the acoustic fields overlap; and in the case of locations separated by significant distances the acoustic fields do not overlap and are aggregated
**Calculated based on the range of the variants accounting for 1 source and 2 sources at the distance of 20 km*
Source: internal data

The results indicate that neighbouring sources generate a much smaller impact area. Locations separated by significant distances, the acoustic fields of which do not overlap, generate the largest impact areas unless the distance is small enough for the impact areas to merge into one common area. A greater surface area between the sources will cumulate with the impact areas as it has been shown in the case of the threshold values for PTS determined by the accumulated noise exposition level resulting from multiple pile driver strikes (1 hour) in locations separated by 20 km. It seems to be a rational solution to work on the assumption about non-overlapping sources and the impact area increased by extra 20% (safety index 1.2) in order to account for the additional impact within the distances separating the sources that involve overlapping acoustic fields (Table 16).

Table 16. Conservative estimates of the area of impact [km²] on porpoises generated by noise from 1, 2, 3 and 4 pile driving locations in the worst case (sources separated by a significant distance)

Threshold value		1 source	2 sources	3 sources	4 sources
impact area [km²]	Behavioural reaction	1950	4680	7020	9360
	TTS (a single pile driver strike)	4.5	10.8	16.2	21.6
	TTS (cumulated impact [1 hour])	1120	2690	4030	5380
	PTS (a single pile driver strike)	0.03	0.08	0.11	0.15
	PTS (cumulated impact [1 hour])	197	475	710	950

The calculated impact areas are the sums of single impact areas increased by 20% (safety index 1.2)
Source: internal data

Conservative estimates on the impact area presented in the table above (Table 16) apply to any distance between the piling locations within the boundaries of the BŚII, BŚIII and Baltica OWFs. What is crucial in the calculations is the number of locations (noise sources). The arrangement of locations is not known; all pilings may be conducted within the area of a single OWF or it may be one piling in each of the OWFs. In each case, the impact area will be the same.

Conservative estimates of the area of impact on harbour porpoises (Table 16) were used in calculating the confidence intervals in the abundance of animals present in a specific area (Table 17). Next, the percentage of animals impacted by noise from pile driving was calculated based on those abundance levels (Table 18).

Table 17. The number of animals within the impact area

Threshold value		1 source	2 sources	3 sources	4 sources
the number of animals	Behavioural reaction	1.2*; 16**	2.3*; 32.1**	3.5*; 48.2**	4.7*; 64.3**
	TTS (a single pile driver strike)	0.3*; 3.7 x 10^{-2}**	0.5*; 7.4 x 10^{-2}**	0.8*; 11.1 x 10^{-2}**	1.1*; 14.8 x 10^{-2}**
	TTS (cumulated impact [1 hour])	0.7*; 9.2**	1.3*;18.3**	2.0*; 27.5**	9.2*; 36.7**
	PTS (a single pile driver strike)	0.2*; 2.5 x 10^{-4}**	0.4*; 4.9 x 10^{-4}**	0.5*; 7.4 x 10^{-4}**	0.7*; 9.9 x 10^{-4}**
	PTS (cumulated impact [1 hour])	0.1*; 1.6**	0.3*; 3.9**	0.4*; 5.8**	0.6*; 7.8**

**lowest estimates*

***conservative estimates*

Source: internal data

Table 18. Percentage of impacted animals in relation to the total population estimated based on the confidence interval (low and high)

Threshold value		1 source	2 sources	3 sources	4 sources
% of impacted animals	Behavioural reaction	1.5	2.9	4.4	5.9
	TTS (a single pile driver strike)	3.4 x 10^{-3}	6.8 x 10^{-3}	10.1 x 10^{-3}	13.5 x 10^{-3}
	TTS (cumulated impact [1 hour])	0.8	1.7	2.5	3.3
	PTS (a single pile driver strike)	2.3 x 10^{-5}	4.5 x 10^{-5}	6.8 x 10^{-5}	9.1 x 10^{-5}
	PTS (cumulated impact [1 hour])	0.15	0.36	0.53	0.71

Source: internal data

The modelling results indicate that piling works conducted in two places at the same time generates only insignificant impact on the harbour porpoise. It means that piling may be conducted in two places in the Baltica OWF Area. Should piling take place in a single location in the BŚII and BŚIII OWFs, another piling may be performed within Baltica OWF but if there are more than two noise sources, a significant impact may occur.

5.2.3 Ichthyofauna

The zones of impact on fish without swim bladder increase with a greater number of noise sources, but they are more dependent on the distance between individual piling locations, It is presented in the maps drawn for a single location (Figure 26, Figure 41), two neighbouring locations (Figure

49Figure 43), two locations separated by 20 km (Figure 50), three locations (Figure 51Figure 48) and in the table (Table 19).

Overlapping acoustic fields in the case of distances of 20 m cause a significant increase in the surface of the impact area as single impact areas of individual sources spread wide along the north-south axis, and all the impact areas between them aggregate, thus making a large accumulated impact area (Figure 50).

What is even more significant is the increase in the PTS impact area based on the SEL_{cum} generated by multiple (1 hour) pile driver strikes, which requires also a 50% safety margin (safety index 1.5).

Generally, the areas of impact on fish without swim bladder were calculated with additional margin of 50% (Table 20). The safety index at the level of 50% may seem an excessive caution but the analyses on fish with swim bladder indicate that this precaution is simply necessary.

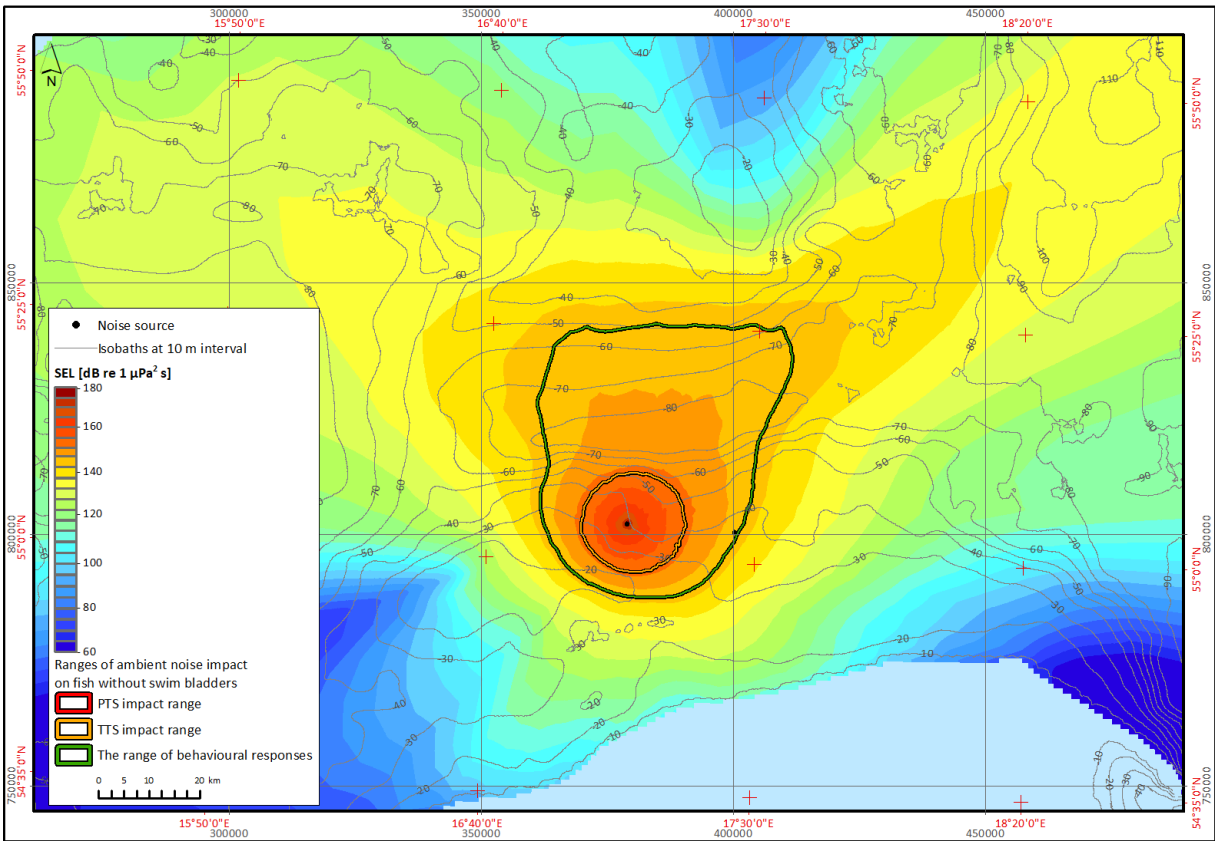

Figure 49. The acoustic map of SEL noise exposition levels (dB re 1 µPa²s) generated by single strikes of pile drivers in two neighbouring locations affecting fish without swim bladder

The ranges of TTS and PTS impacts based on SEL_{cum}
Source: internal data

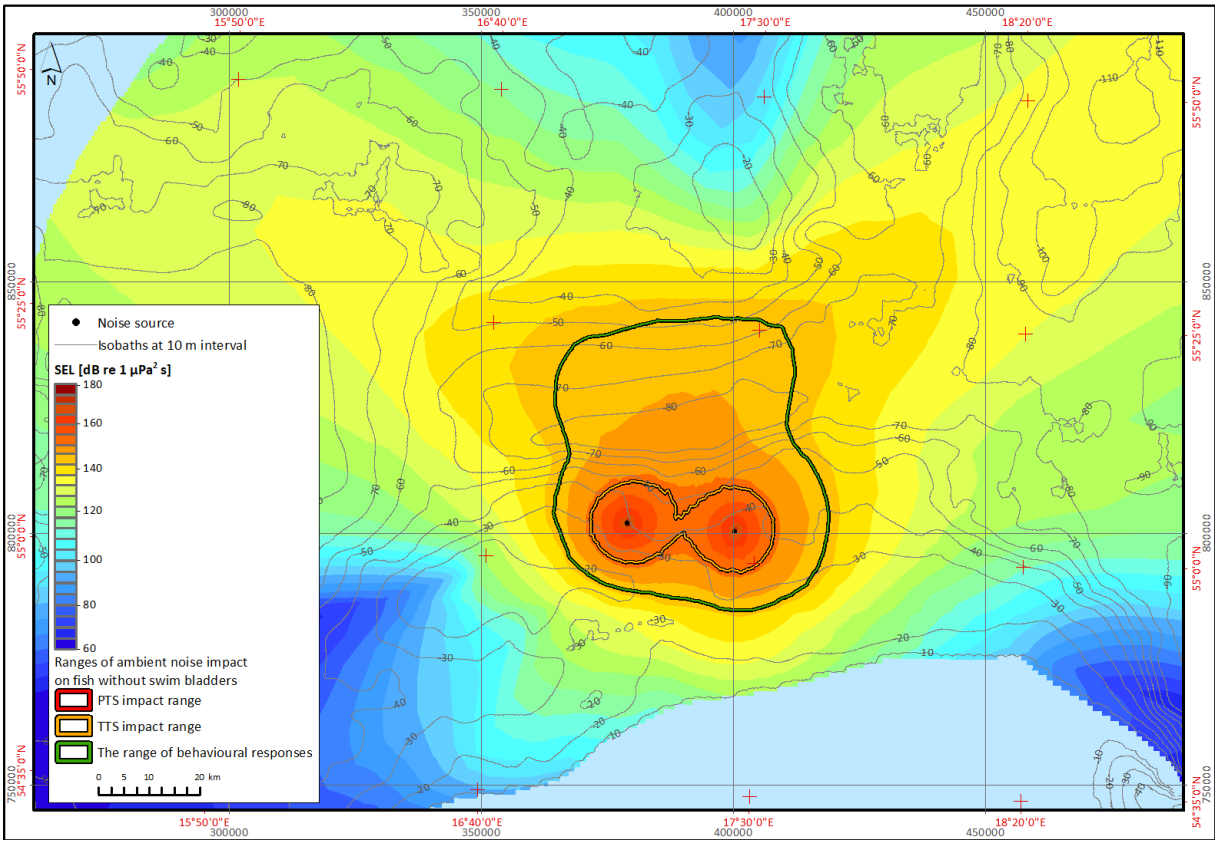

Figure 50. The acoustic map of SEL noise exposition levels (dB re 1 µPa²s) generated by single strikes of pile drivers in locations separated by 20 km affecting fish without swim bladder

The ranges of TTS and PTS impacts based on SEL_{cum}

Source: internal data

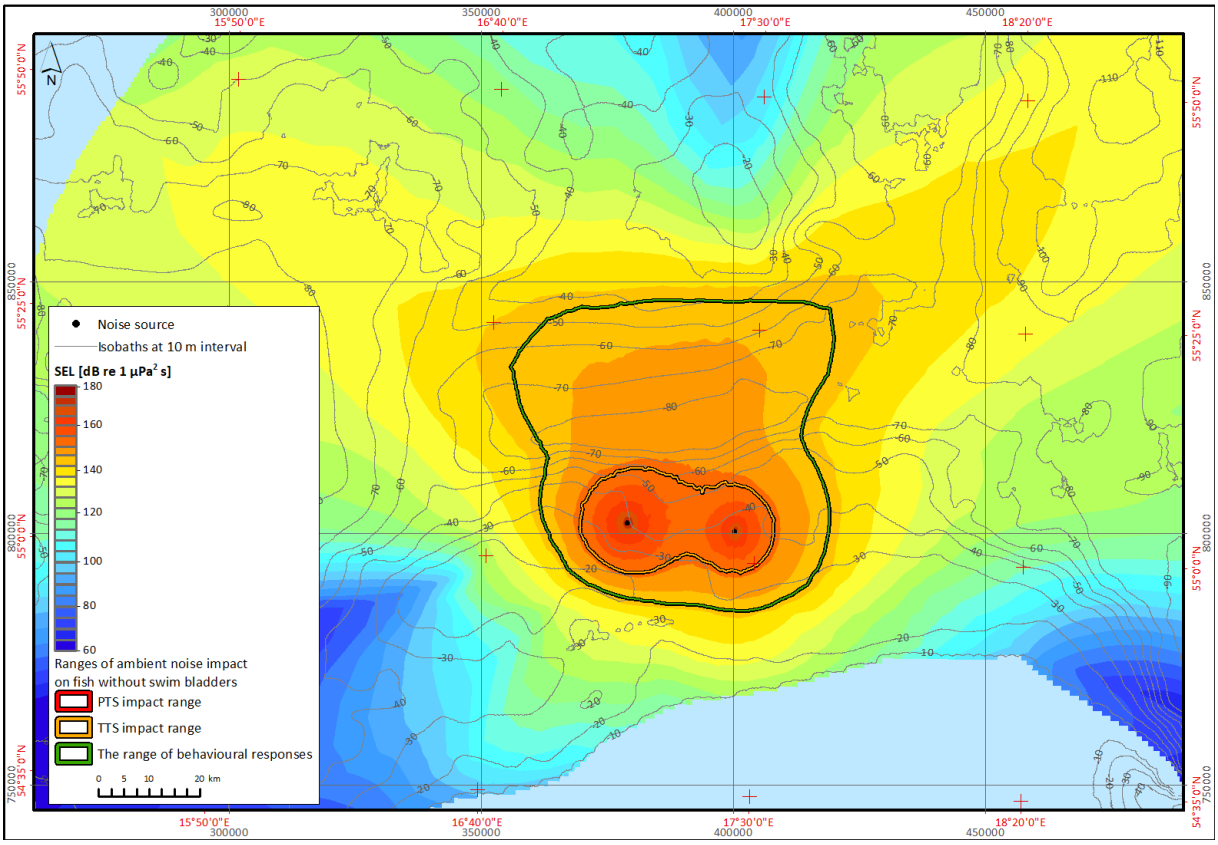

Figure 51. The acoustic map of SEL noise exposition levels (dB re 1 µPa²s) generated by single strikes of pile drivers in three locations (2 neighbouring in the western part of the area and one at the distance of 20 km) affecting fish without swim bladder

The ranges of TTS and PTS impacts based on SEL_{cum}

Source: internal data

Table 19. The ranges of impact [km] on fish without swim bladder for noise from 1, 2 and 3 sources

SEL threshold value (dB re 1 µPa²s)		1 source	2 sources (2 neighbouring sources)	2 sources (2 sources at the distance of 20 km)	2 sources (2 sources at a significant distance)	3 sources (2 neighbouring sources/ 1 source at the distance of 20 km)	3 sources (2 at the distance of 20 km/ 1 source at a significant distance)
the average distance [km]	Behavioural reaction	18.6	24.7	26.1	37.2	29.4	44.7
	TTS (a single pile driver strike)	0.1	0.1	0.1	0.2	0.1	0.2
	TTS (cumulated impact [1 hour])	8.0	10.5	10.8	16.0	12.9	18.8
	PTS (a single pile driver strike)	0.1	0.1	0.1	0.2	0.1	0.2
	PTS (cumulated impact [1 hour])	0.1	0.2	0.1	0.2	0.2	0.2
the maximum distance [km]	Behavioural reaction	32.6	52.5	50.2	65.2	59.9	82.8
	TTS (a single pile driver strike)	0.1	0.1	0.1	0.2	0.1	0.2
	TTS (cumulated impact [1 hour])	9.2	12.7	29.5	18.4	29.5	38.7

SEL threshold value (dB re 1 µPa²s)		1 source	2 sources (2 neighbouring sources)	2 sources (2 sources at the distance of 20 km)	2 sources (2 sources at a significant distance)	3 sources (2 neighbouring sources/ 1 source at the distance of 20 km)	3 sources (2 at the distance of 20 km/ 1 source at a significant distance)
	PTS (a single pile driver strike)	0.1	0.1	0.1	0.2	0.1	0.2
	PTS (cumulated impact [1 hour])	0.1	0.2	0.1	0.2	0.2	0.2
impact area [km²]	Behavioural reaction	1210	2324	2663	2420	3334	3873
	TTS (a single pile driver strike)	0.03	0.03	0.03	0.06	0.03	0.06
	TTS (cumulated impact [1 hour])	204	348	500	408	630	704
	PTS (a single pile driver strike)	0.03	0.03	0.03	0.06	0.06	0.06
	PTS (cumulated impact [1 hour])	0.03	0.1	0.03	0.06	0.1	0.06

The threshold values are related to the exposition levels and they do not account for the weight
In the simulations, the distance between the sources was established at 0 km in the case of neighbouring locations; for those located at the distance of 20 km it is simulated that the acoustic fields overlap; and in the case of locations separated by significant distances, the acoustic fields do not overlap and are aggregated
**Calculated based on the range of the variants accounting for 1 source and 2 sources at the distance of 20 km*
Source: internal data

Table 20. Conservative estimates of the impact area [km²] for fish without swim bladder affected by noise from 1, 2, 3 and 4 pile driving locations in the worst-case scenario (sources located at a significant distance)

Threshold value		1 source	2 sources	3 sources	4 sources
impact area [km²]	Behavioural reaction	1210	3630	5445	7260
	TTS (a single pile driver strike)	0.03	0.1	0.2	0.2
	TTS (cumulated impact [1 hour])	204	612	920	1224
	PTS (a single pile driver strike)	0.03	0.1	0.2	0.2
	PTS (cumulated impact [1 hour])	0.03	0.1	0.2	0.2

The calculated impact areas are the sums of single impact areas increased by 50% (safety index 1.5)
Source: internal data

The range of impact on fish with swim bladders increases with the number of noise sources. It has been presented in the maps drawn for a single location (Figure 27, Figure 42), two neighbouring locations (Figure 52), two locations separated by 20 km (Figure 53), three locations (Figure 54), as well as in the table (Table 21). In the case of behavioural reaction, the observed impact area was significantly larger. The areas of impact on fish with swim bladders share certain characteristics with the areas of impact on fish without swim bladders and harbour porpoises:

- the impact area associated with PTS and TTS resulting from SEL_{cum} caused by multiple (1 hour) strikes of a pile driver is similar as in the case of the harbour porpoise and it is enclosed within a single area for the locations separated by 20 km (Figure 53). As a result, the

threshold values recorded for the area are very high and the reach of impact is long in this particular case (Table 21);

- just like in the case of fish without swim bladders, neighbouring sources increase PTS significantly based on SEL_{cum} resulting from multiple (1 hour) strikes of a pile driver but the impact area is relatively small – 7.1 km² – and so the safety index should be applied in relation to this zone.

The areas of impact on fish with swim bladders have been calculated with an additional margin of 50% (Table 22).

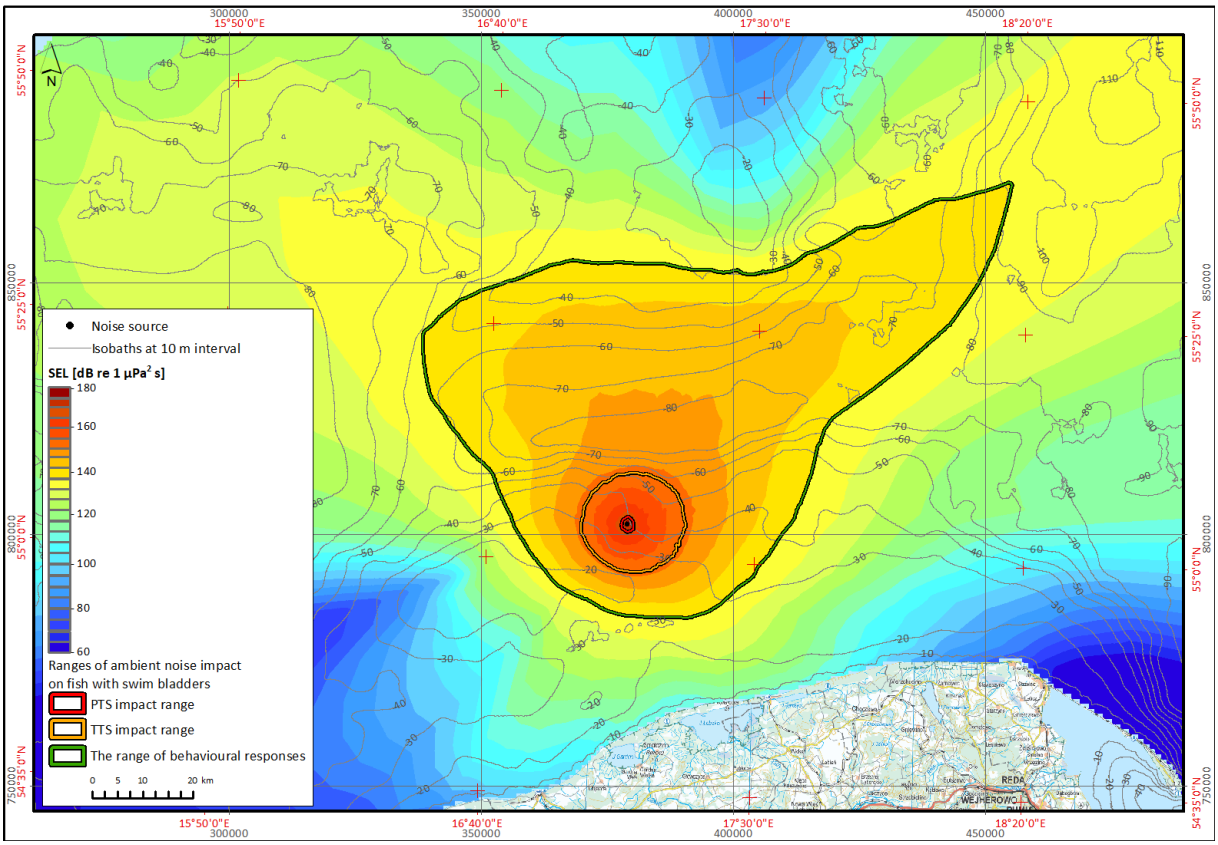

Figure 52. The acoustic map of SEL noise exposition levels (dB re 1 µPa²s) generated by single strikes of pile drivers in two neighbouring locations as affecting fish with swim bladders

The ranges of TTS and PTS impacts based on SEL_{cum}
Source: internal data

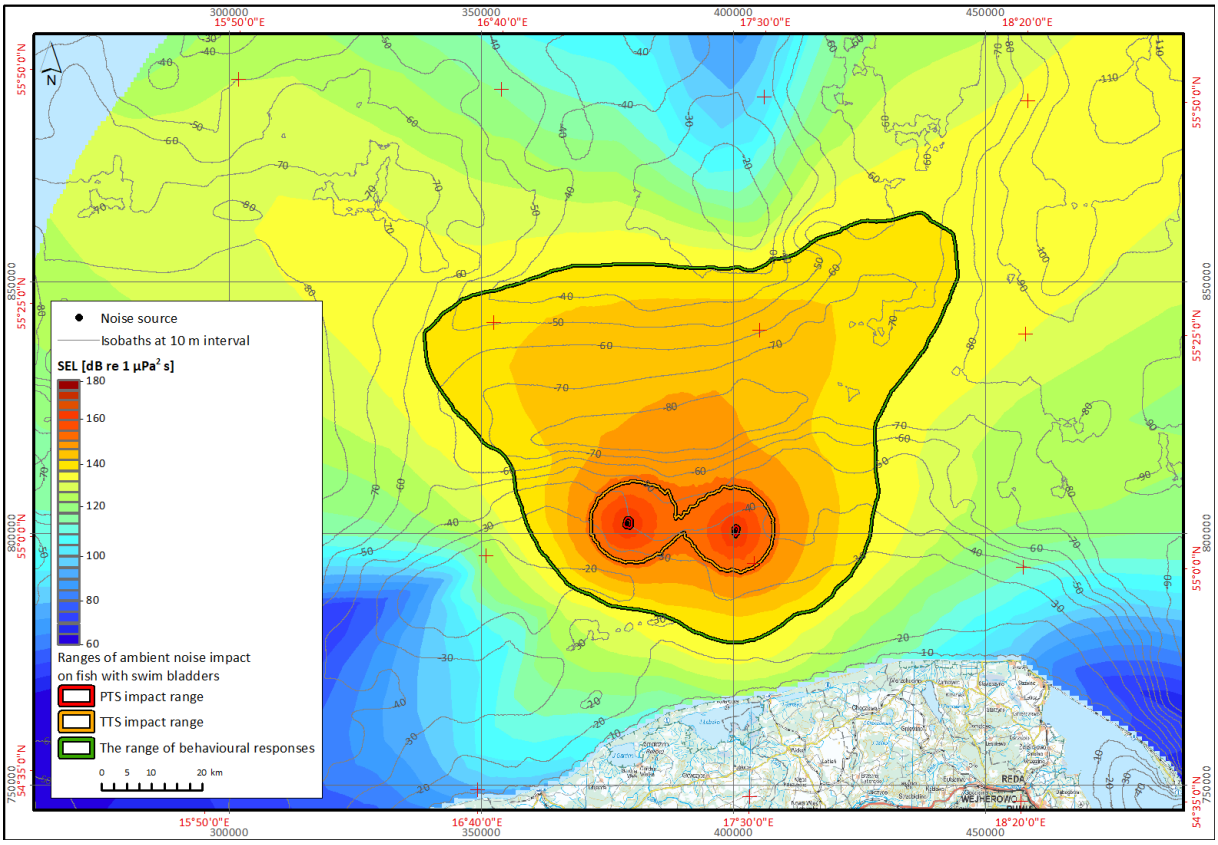

Figure 53. The acoustic map of SEL noise exposition levels (dB re 1 µPa²s) generated by single strikes of pile drivers in locations separated by 20 km as affecting fish with swim bladders

The ranges of TTS and PTS impacts based on SEL_{cum}

Source: internal data

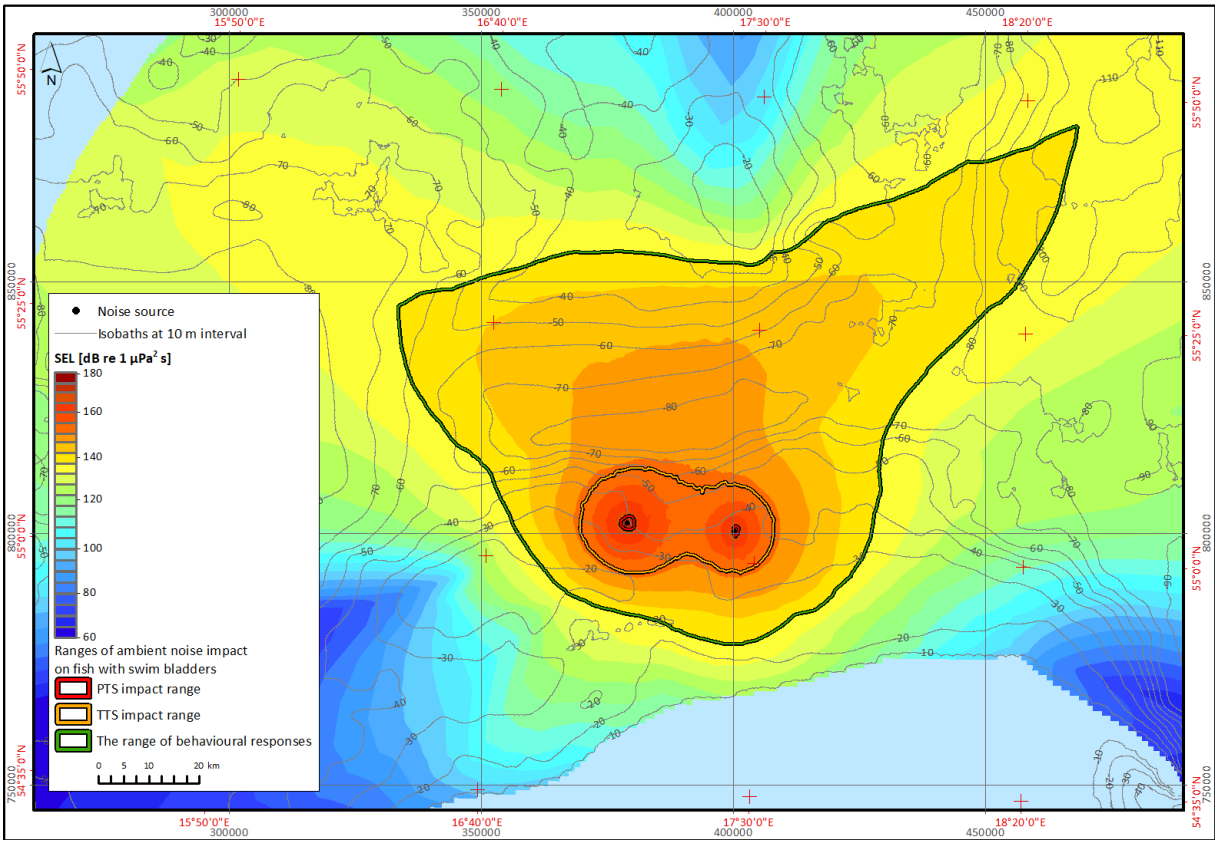

Figure 54. The acoustic map of SEL noise exposition levels (dB re 1 µPa²s) generated by single strikes of pile drivers in three locations (2 neighbouring and one at the distance of 20 km) as affecting fish with swim bladders

The ranges of TTS and PTS impacts based on SEL_{cum}

Source: internal data

Table 21. The range of impact [km] on fish with swim bladders for noise from 1, 2 and 3 sources

SEL threshold value (dB re 1 µPa²s)		1 source	2 sources (2 neighbouring sources)	2 sources (2 sources at the distance of 20 km)	2 sources (2 sources at a significant distance)	3 sources (2 neighbouring sources/ 1 source at the distance of 20 km)	3 sources (2 sources at the distance of 20 km/ 1 source at a significant distance
the average distance [km]	Behavioural reaction	31.7	36.7	38.5	**63.4**	42.1	**68.4**
	TTS (a single pile driver strike)	0.1	0.1	0.1	**0.2**	0.1	**0.2**
	TTS (cumulated impact [1 hour])	8.0	10.5	10.8	**16.0**	12.9	**18.5**
	PTS (a single pile driver strike)	0.1	0.1	0.1	**0.2**	0.1	**0.2**
	PTS (cumulated impact [1 hour])	0.9	1.5	0.9	**1.8**	1.5	**2.4**
the maximum distance	Behavioural reaction	76.2	104	87.9	**152.4**	123.1	**180**
	TTS (a single pile	0.1	0.1	0.1	**0.2**	0.1	**0.2**

SEL threshold value (dB re 1 µPa²s)		1 source	2 sources (2 neighbouring sources)	2 sources (2 sources at the distance of 20 km)	2 sources (2 sources at a significant distance)	3 sources (2 neighbouring sources/ 1 source at the distance of 20 km)	3 sources (2 sources at the distance of 20 km/ 1 source at a significant distance
	driver strike)						
	TTS (cumulated impact [1 hour])	9.2	12.7	**29.5**	18.4	**29.5**	21.9
	PTS (a single pile driver strike)	0.1	0.1	0.1	**0.2**	0.1	**0.2**
	PTS (cumulated impact [1 hour])	1.0	1.7	1.0	**2**	1.7	**2.7**
impact area [km²]	Behavioural reaction	4005	5535	5868	**8010**	7257	**9540**
	TTS (a single pile driver strike)	0.03	0.03	0.03	**0.06**	0.03	**0.06**
	TTS (cumulated impact [1 hour])	204	348	**500**	408	**630**	552
	PTS (a single pile driver strike)	0.03	0.03	0.03	**0.06**	0.03	**0.06**
	PTS (cumulated impact [1 hour])	2.4	**7.1**	2.4	4.8	7.1	**9.5**

The threshold values are related to the exposition levels and they do not account for the weight
In the simulations, the distance between the sources was established at 0 km in the case of neighbouring locations; for those located at the distance of 20 km it is simulated that the acoustic fields overlap; and in the case of locations separated by significant distances the acoustic fields do not overlap and are aggregated
**Calculated based on the range of the variants accounting for 1 source and 2 sources at the distance of 20 km*
Source: internal data

Table 22. Conservative estimates of the impact area [km²] for fish with swim bladders affected by noise from 1, 2, 3 and 4 locations of pile driving in the worst-case scenario (sources located at a significant distance)

Threshold value		1 source	2 sources	3 sources	4 sources
impact area [km²]	Behavioural reaction	4005	12000	18000	24000
	TTS (a single pile driver strike)	0.03	0.1	0.2	0.2
	TTS (cumulated impact [1 hour])	204	612	920	1224
	PTS (a single pile driver strike)	0.03	0.1	0.2	0.2
	PTS (cumulated impact [1 hour])	2.4	7.2	10.8	14.4

The calculated impact areas are the sums of single impact areas increased by 50% (safety index 1.5)
Source: internal data

5.3 Simulation of the noise accumulation with the noise generated by other OWFs

In order to verify the range of the accumulated noise impact from the Baltica and other OWFs, 2 simultaneous pilings have been simulated for different combinations of pairs from the following locations:

1) the central point of the BŚII OWF,
2) the central point of the Baltica 2 Area,

3) the central point of the Baltica 3 Area, and
4) the central point of the BŚIII OWF.

The surface areas of the SEL levels have been calculated in accordance with the instructions presented in section 5.1.2 for all 10 combinations of possible pairs of locations – BŚII and BŚII; BŚII and Baltica 2; BŚII and Baltica 3, BŚII and BŚIII; Baltica 2 and Baltica 2; Baltica 2 and Baltica 3; Baltica 2 and BŚII; Baltica 3 and Baltica 3; Baltica 3 and BŚIII; BŚIII and BŚIII. Next, the 10 noise fields identified have been analysed, and the highest possible noise level was determined in each mesh node of a rectangular grid with 250 m side. The maximum unweighted and HF and PW-weighted SEL values allowed determining the ranges of behavioural response and TTS and PTS impact on harbour porpoises, seals and ichthyofauna. The results are presented in the figures below (Figure 55, Figure 56, Figure 57, Figure 58).

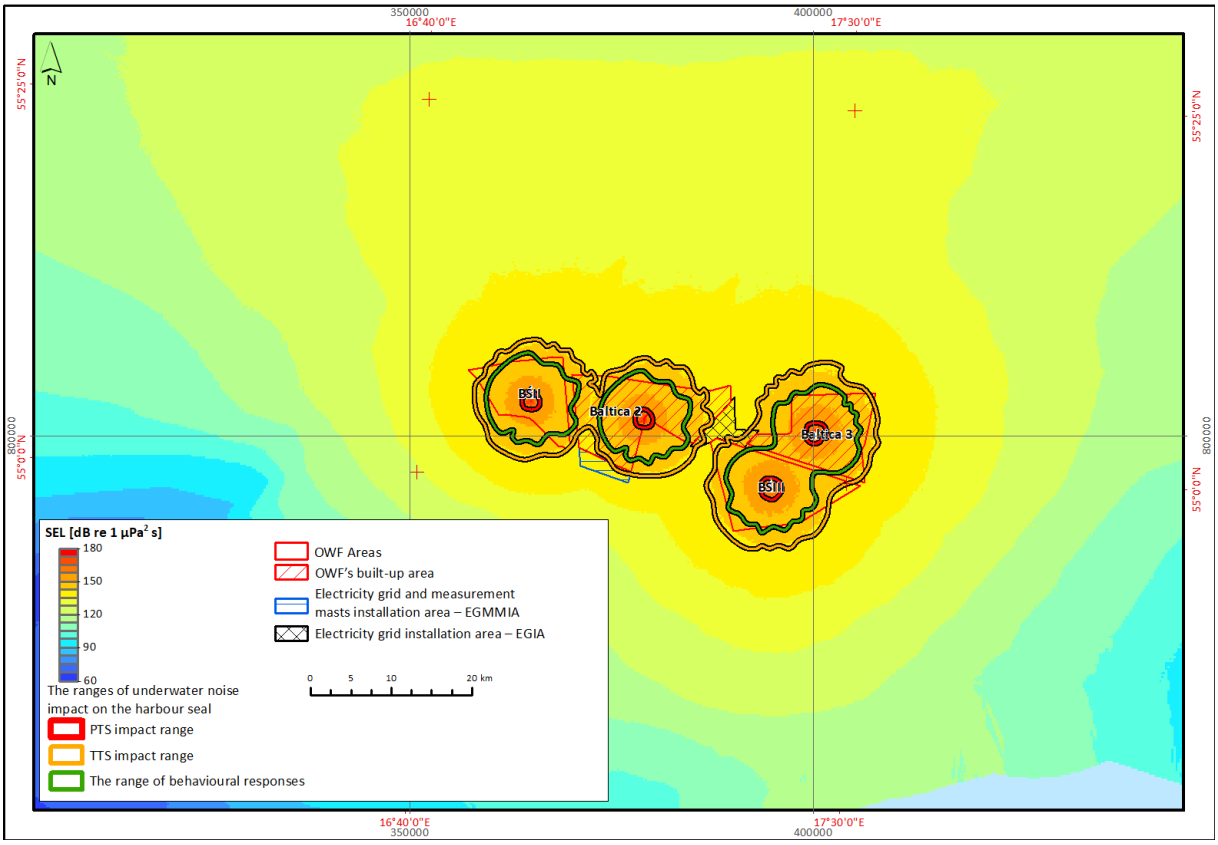

Figure 55. The maximum ranges of the noise impact on seals from pile driving conducted simultaneously in two places in the Baltica, BŚII and BŚIII OWFs (PW-weighted SEL)

The ranges of TTS and PTS impacts based on SEL_{cum}

Source: internal data

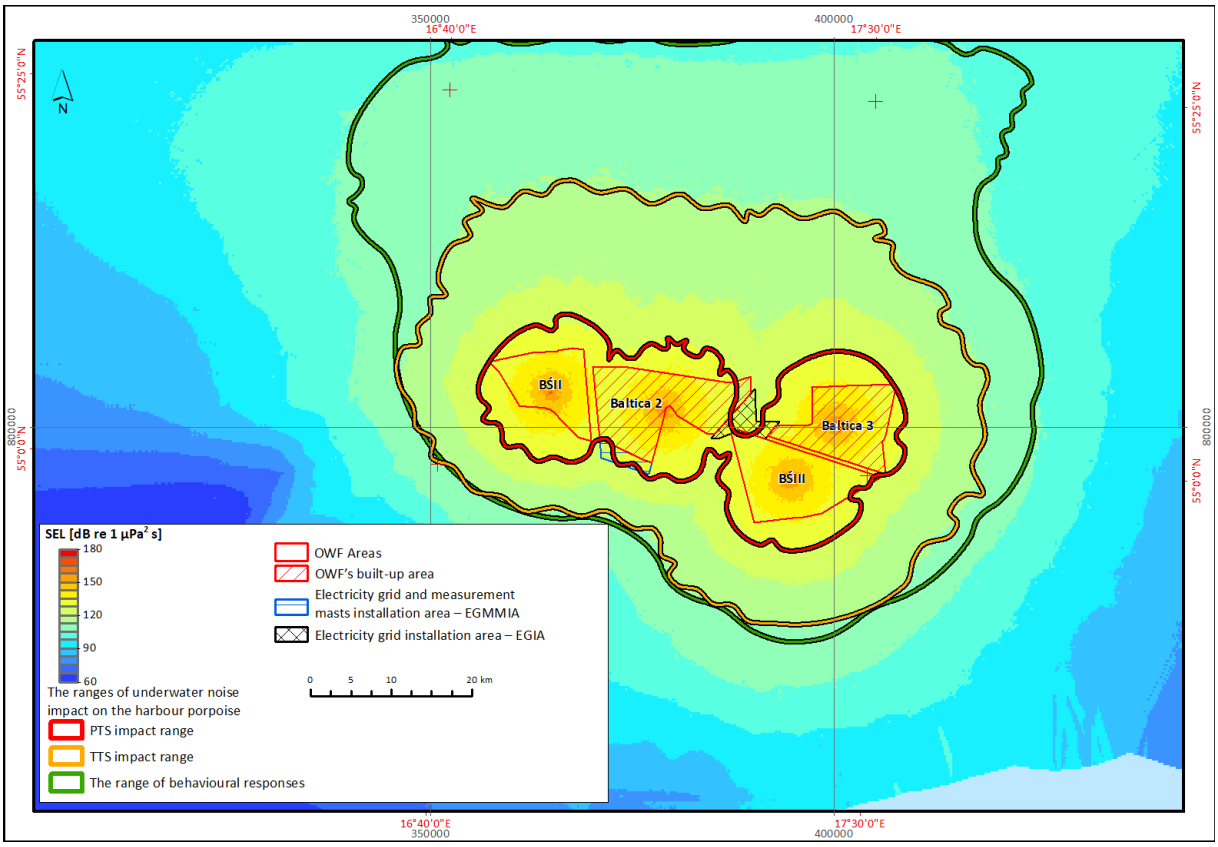

Figure 56. The maximum ranges of the noise impact on the harbour porpoise from pile driving conducted simultaneously in two places in the Baltica, BŚII and BŚIII OWFs (HF-weighted SEL)

The ranges of TTS and PTS impacts based on SEL_{cum}

Source: internal data

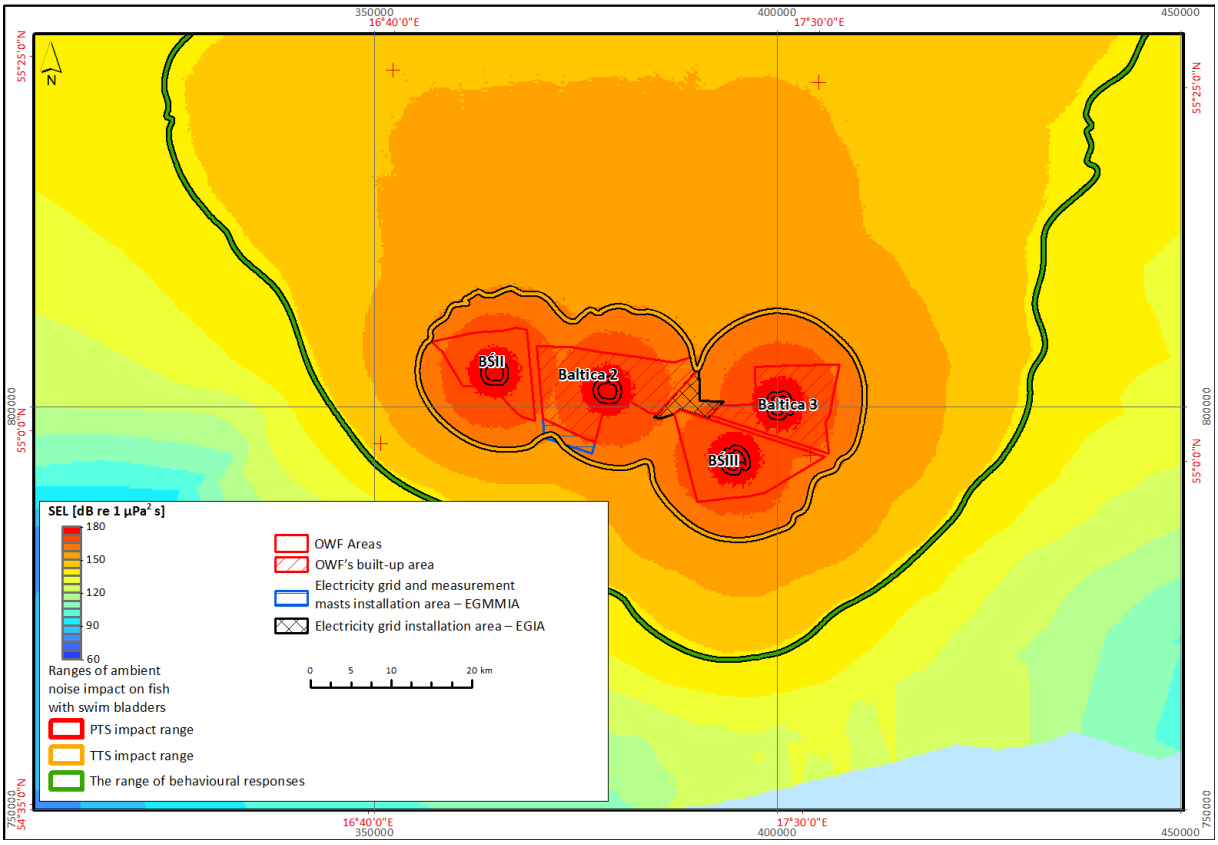

Figure 57. The maximum ranges of the noise impact on fish with swim bladders from pile driving conducted simultaneously in two places in the Baltica, BŚII and BŚIII OWFs (unweighted SEL)

The ranges of TTS and PTS impacts based on SEL_{cum}

Source: internal data

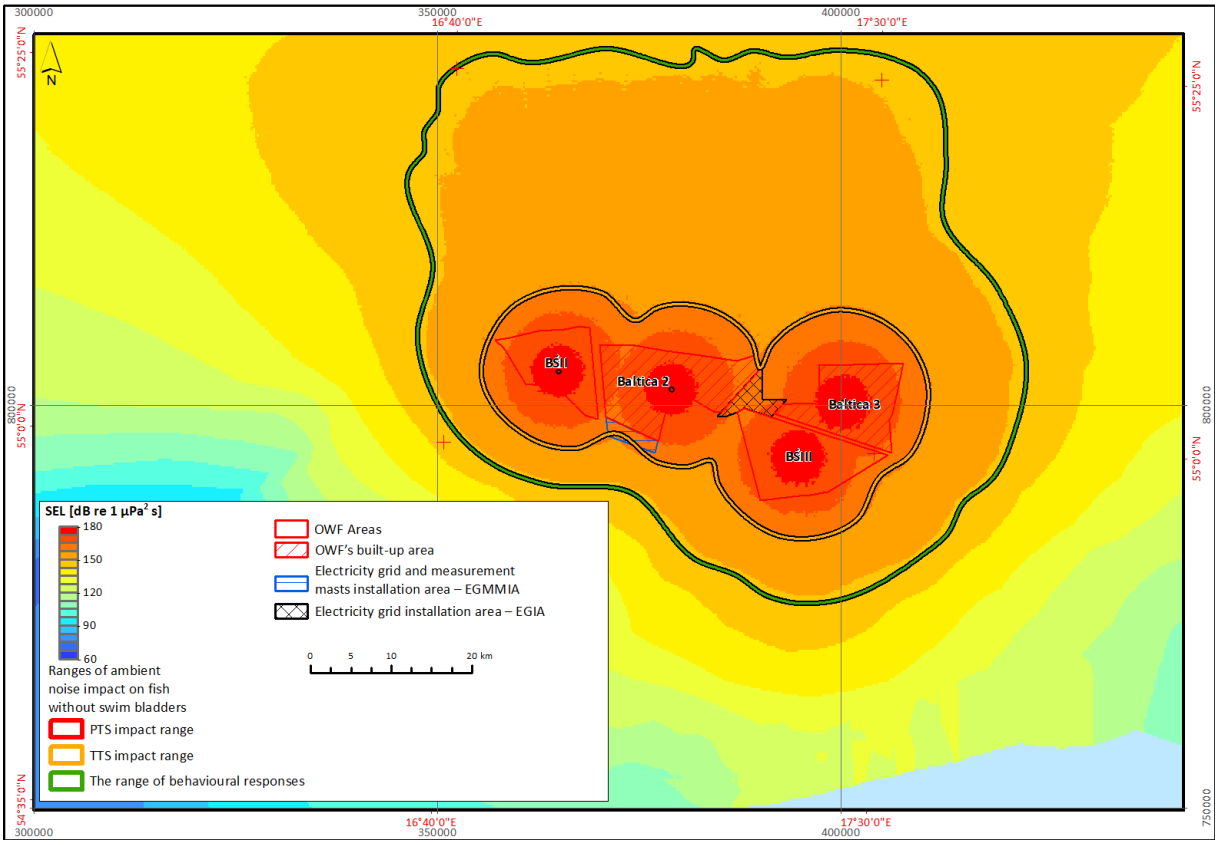

Figure 58. The maximum ranges of the noise impact on fish without swim bladders from pile driving conducted simultaneously in two places in the Baltica, BŚII and BŚIII OWFs (unweighted SEL)

Source: internal data

6 Summary

6.1 Noise propagation from pile driving in a single location

6.1.1 The impact zone of the pile driving in the Baltica 2 Area

The table below (Table 23) compares the impact zones of the pile driving in the Baltica 2 Area with respect to seals, porpoises and ichthyofauna.

Table 23. The impact zones of the pile driving in the Baltica 2 Area [km^2] with respect to seals, porpoises and ichthyofauna

Threshold value	Grey and harbour seals	Porpoises	Fish without swim bladders	Fish with swim bladders
Behavioural reaction	49.3	1953	1210	4005
TTS (a single pile driver strike)	0.03	4.5	0.03	0.03
TTS (cumulated impact [1 hour])	99.5	1114	204	204
PTS (a single pile driver strike)	0.03	0.03	0.03	0.03
PTS (cumulated impact [1 hour])	1.7	197	0.03	2.4

Source: internal data

6.1.2 The impact zone of the pile driving in the Baltica 3 Area

The table below (Table 24) compares the impact zones of the pile driving in the Baltica 3 Area with respect to seals, porpoises and ichthyofauna.

Table 24. The impact zones of the pile driving in the Baltica 3 Area [km^2] with respect to seals, porpoises and ichthyofauna

Threshold value	Grey and harbour seals	Porpoises	Fish without swim bladders	Fish with swim bladders
Behavioural reaction	52.6	2061	1324	4146
TTS (a single pile driver strike)	0.03	4.9	0.03	0.03
TTS (cumulated impact [1 hour])	116	1173	211	211
PTS (a single pile driver strike)	0.03	0.03	0.03	0.03
PTS (cumulated impact [1 hour])	2.1	191	0.03	3.5

Source: internal data

6.2 Noise propagation from pile driving works performed in several locations

The table below (Table 25) compares the modelled ranges of impact on seals, porpoises and ichthyofauna during piling works conducted in up to 4 locations at a significant distance form one another based on the simulation of noise propagation generated by a single pile driver strike.

Table 25. Conservative estimates of the surface area affected by the accumulated impact [km^2] of the noise from 1, 2, 3 and 4 pile driving locations in the worst-case scenario (noise sources located at a significant distance)

Threshold value		1 source	2 sources	3 sources	4 sources
porpoises	Behavioural reaction	1953	3906	5859	7812
	TTS (a single pile driver strike)	4.5	9.0	13.5	18.0
	TTS (cumulated impact [1 hour])	1114	2228	3342	4456
	PTS (a single pile driver strike)	0.03	0.06	0.09	0.12
	PTS (cumulated impact [1 hour])	197	475	710	950
seals	Behavioural reaction	49.3	120	178	237
	TTS (a single pile driver strike)	0.03	0.1	0.1	0.2
	TTS (cumulated impact [1 hour])	99.5	240	360	480
	PTS (a single pile driver strike)	0.03	0.1	0.1	0.2
	PTS (cumulated impact [1 hour])	1.7	4.1	6.1	8.2
fish with swim bladders	Behavioural reaction	1210	3630	5445	7260
	TTS (a single pile driver strike)	0.03	0.1	0.2	0.2
	TTS (cumulated impact [1 hour])	204	612	920	1224
	PTS (a single pile driver strike)	0.03	0.1	0.2	0.2
	PTS (cumulated impact [1 hour])	0.03	0.1	0.2	0.2
without swim bladder	Behavioural reaction	4005	12000	18000	24000
	TTS (a single pile driver strike)	0.03	0.1	0.2	0.2

Threshold value		1 source	2 sources	3 sources	4 sources
	TTS (cumulated impact [1 hour])	204	612	920	1224
	PTS (a single pile driver strike)	0.03	0.1	0.2	0.2
	PTS (cumulated impact [1 hour])	2.4	7.2	10.8	14.4

In order to account for all the spatial combinations (distances between the sources), the results obtained for each combination were increased by the adequate value of the caution/safety index: the marine mammals (porpoises, grey seals and harbour seals) – index value 1.2; fish – index value 1.5
Source: internal data

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8 List of tables

Table 1. Geoacoustic parameters of the seabed used in the acoustic modelling 14
Table 2. Underwater sound emissions from pile driving..... 16
Table 3. The criteria for noise exposition applied when calculating the impact range 25
Table 4. Functional hearing groups and associated with them hearing channels 26
Table 5. The noise impact range in the case of grey and harbour seals 34
Table 6. The impact ranges in the case of porpoises. 36
Table 7. The impact ranges in the case of fish without the swim bladder..... 37
Table 8. The impact ranges in the case of fish with the swim bladder 38
Table 9. The impact ranges in the case of grey and harbour seals 46
Table 10. The impact ranges in the case of porpoises 48
Table 11. The impact ranges in the case of fish without the swim bladder..... 49
Table 12. The impact ranges in the case of fish with the swim bladder 50
Table 13. The impact ranges [km] for seals for the noise from sources 1, 2 and 3..... 55
Table 14. Conservative estimates of the area of impact [km^2] on seals generated by noise from 1, 2, 3 and 4 pile driving locations in the worst case (sources separated by a significant distance)..... 56
Table 15. The area of impact [km] on harbour porpoises for noise from 1, 2 and 3 sources..... 59
Table 16. Conservative estimates of the area of impact [km^2] on porpoises generated by noise from 1, 2, 3 and 4 pile driving locations in the worst case (sources separated by a significant distance) 60
Table 17. The number of animals within the impact area 61
Table 18. Percentage of impacted animals in relation to the total population estimated based on the confidence interval (low and high)..... 61
Table 19. The ranges of impact [km] on fish without swim bladder for noise from 1, 2 and 3 sources..... 64
Table 20. Conservative estimates of the impact area [km^2] for fish without swim bladder affected by noise from 1, 2, 3 and 4 pile driving locations in the worst-case scenario (sources located at a significant distance) 65
Table 21. The range of impact [km] on fish with swim bladders for noise from 1, 2 and 3 sources 68
Table 22. Conservative estimates of the impact area [km^2] for fish with swim bladders affected by noise from 1, 2, 3 and 4 locations of pile driving in the worst-case scenario (sources located at a significant distance) 69
Table 23. The impact zones of the pile driving in the Baltica 2 Area [km^2] with respect to seals, porpoises and ichthyofauna 73
Table 24. The impact zones of the pile driving in the Baltica 3 Area [km^2] with respect to seals, porpoises and ichthyofauna 74
Table 25. Conservative estimates of the surface area affected by the accumulated impact [km^2] of the noise from 1, 2, 3 and 4 pile driving locations in the worst-case scenario (noise sources located at a significant distance)..... 74

9 List of figures

Figure 1. Spectral noise level in relation to the strike energy 8
Figure 2. The sites of the Baltica 2 Area and the Baltica 3 Area along with the site of the modelled sound sources constituting the central points 9
Figure 3. Directions of the sound propagation modelling in the Baltica 2 Area 10
Figure 4. Directions of the sound propagation modelling in the Baltica 3 Area 11
Figure 5. Seasonal changes of salinity, temperature and sound velocity..... 12
Figure 6. Seasonal changes within the pH range 14
Figure 7. A diagram of propagating acoustic wave from the deep to the shallow waters and the increase of interaction with the seabed and the surface of water 16
Figure 8. The model frequency spectra of the sound generated during piling in 1/3 octave-bands 18
Figure 9. The absorption coefficient from the model of Francois and Garrison (1982a, 1982b) used in the MIKE UAS in comparison to the model of Richards et al. (1995) 21
Figure 10. The SEL reduction in relation to the frequencies for the three various noise mitigation systems: the single bubble curtain Big Bubble Curtain (BBC), the double bubble curtain Big Bubble Curtain (DBBC) and the noise reduction screen IHC (IHC)..... 22
Figure 11. Transmission loss from the simulation MIKE UAS in two transects selected from the Baltica 2 Area 23
Figure 12. Spectrum transmission loss after extrapolation along two selected transects in the Baltica 2 Area 24
Figure 13. The applied HF and PW weights in comparison to the M-weight for marine mammals in water 27
Figure 14. The acoustic map of the noise exposure level SEL (dB re 1 $\mu Pa^2 s$) caused by a single strike of a pile driver in the Baltica 2 Area..... 28
Figure 15. The model of the sound propagation along the transect 1 – the sound exposure level SEL (dB re 1 $\mu Pa^2 \cdot s$) for a single strike of a pile driver..... 29
Figure 16. The sound propagation model along the transect 2 – noise exposure level SEL (dB re 1 $\mu Pa^2 \cdot s$) in the case of a single strike of a pile driver 29
Figure 17. The model of the sound propagation along the transect 3 – the sound exposure level SEL (dB re 1 $\mu Pa^2 \cdot s$) for a single strike of a pile driver..... 30
Figure 18. The model of the sound propagation along the transect 4 – the sound exposure level SEL (dB re 1 $\mu Pa^2 \cdot s$) for a single strike of a pile driver..... 30
Figure 19. The model of the sound propagation along transect 5 – the sound exposure level SEL (dB re 1 $\mu Pa^2 \cdot s$) for a single strike of a pile driver 31
Figure 20. The model of the sound propagation along transect 6 – the sound exposure level SEL (dB re 1 $\mu Pa^2 \cdot s$) for a single strike of a pile driver 31
Figure 21. The summary of the maximum SELs during a single strike with a pile driver along designated transects..... 32

Figure 22. The acoustic map of the weighted (PW) noise exposure level SEL (dB re 1 μPa^{2}s) caused by a single strike of a pile driver in the Baltica 2 Area 33
Figure 23. Acoustic map of the sound pressure level SPL_{peak} in the Baltica 2 Area 34
Figure 24. The acoustic map of the weighted (HF) noise exposure level SEL (dB re 1 μPa^{2}s) caused by a single strike of a pile driver in the Baltica 2 Area 35
Figure 25. Acoustic map of the sound pressure level SPL_{peak} taking into account the threshold values in the Baltica 2 Area 36
Figure 26. The acoustic map of the noise exposure level SEL (dB re 1 μPa^{2}s) caused by a single strike of a pile driver in the Baltica 2 Area in the case of fish without the swim bladder 37
Figure 27. The acoustic map of the noise exposure level SEL (dB re 1 μPa^{2}s) caused by a single strike of a pile driver in the Baltica 2 Area in the case of fish with the swim bladder 38
Figure 28. The acoustic map of the noise exposure level SEL (dB re 1 μPa^{2}s) caused by a single strike of a pile driver in the Baltica 3 Area 39
Figure 29. The model of the sound propagation along transect 1 – the sound exposure level SEL (dB re 1 μPa^2·s) for a single strike of a pile driver 40
Figure 30. The model of the sound propagation along transect 2 – the sound exposure level SEL (dB re 1 μPa^2·s) for a single strike of a pile driver 40
Figure 31. The model of the sound propagation along transect 3 – the sound exposure level SEL (dB re 1 μPa^2·s) for a single strike of a pile driver 41
Figure 32. The model of the sound propagation along transect 4 – the sound exposure level SEL (dB re 1 μPa^2·s) for a single strike of a pile driver 41
Figure 33. The model of the sound propagation along transect 5 – the sound exposure level SEL (dB re 1 μPa^2·s) for a single strike of a pile driver 42
Figure 34. The model of the sound propagation along transect 6 – the sound exposure level SEL (dB re 1 μPa^2·s) for a single strike of a pile driver 42
Figure 35. The model of the sound propagation along transect 7 – the sound exposure level SEL (dB re 1 μPa^2·s) for a single strike of a pile driver 43
Figure 36. The summary of the maximum SELs during a single strike with a pile driver along designated transects 44
Figure 37. The acoustic map of the weighted (PW) noise exposure level SEL (dB re 1 μPa^{2}s) caused by a single strike of a pile driver in the Baltica 3 Area 45
Figure 38. Acoustic map of the sound pressure level SPL_{peak} taking into account the threshold values in the Baltica 3 Area 46
Figure 39. The acoustic map of the weighted (HF) noise exposure level SEL (dB re 1 μPa^{2}s) caused by a single strike of a pile driver in the Baltica 3 Area 47
Figure 40. Acoustic map of the sound pressure level SPL_{peak} taking into account the threshold values in the Baltica 3 Area 48
Figure 41. The acoustic map of the noise exposure level SEL (dB re 1 μPa^{2}s) caused by a single strike of a pile driver in the Baltica 3 Area in the case of fish without the swim bladder 49
Figure 42. The acoustic map of the noise exposure level SEL (dB re 1 μPa^{2}s) caused by a single strike of a pile driver in the Baltica 3 Area in the case of fish with the swim bladder 50

Figure 43. The acoustic map of the weighted (PW) noise exposure level SEL (dB re 1 μPa^{2}s) triggered by a single strike of a pile driver in two locations close to each other 53
Figure 44. The acoustic map of the weighted (PW) noise exposure level SEL (dB re 1 μPa^{2}s) triggered by a single strike of a pile driver in two locations at the distance of 20 km from each other 54
Figure 45. The acoustic map of the weighted (PW) noise exposure level SEL (dB re 1 μPa^{2}s) caused by a single strike of a pile driver in three locations (two neighbouring and one 20 km away)..... 55
Figure 46. Acoustic map of HF-weighted SEL noise exposition level (dB re 1 μPa^{2}s) generated by single strikes of pile drivers in two neighbouring locations within the Baltica OWF 57
Figure 47. Acoustic map of HF-weighted SEL noise exposition level (dB re 1 μPa^{2}s) generated by single strikes of pile drivers in two locations separated by 20 km 58
Figure 48. Acoustic map of HF-weighted SEL noise exposition level (dB re 1 μPa^{2}s) generated by single strikes of pile drivers in three locations (two neighbouring and one at the distance of 20 km) 59
Figure 49. The acoustic map of SEL noise exposition levels (dB re 1 μPa^{2}s) generated by single strikes of pile drivers in two neighbouring locations affecting fish without swim bladder 62
Figure 50. The acoustic map of SEL noise exposition levels (dB re 1 μPa^{2}s) generated by single strikes of pile drivers in locations separated by 20 km affecting fish without swim bladder 63
Figure 51. The acoustic map of SEL noise exposition levels (dB re 1 μPa^{2}s) generated by single strikes of pile drivers in three locations (2 neighbouring in the western part of the area and one at the distance of 20 km) affecting fish without swim bladder 64
Figure 52. The acoustic map of SEL noise exposition levels (dB re 1 μPa^{2}s) generated by single strikes of pile drivers in two neighbouring locations as affecting fish with swim bladders 66
Figure 53. The acoustic map of SEL noise exposition levels (dB re 1 μPa^{2}s) generated by single strikes of pile drivers in locations separated by 20 km as affecting fish with swim bladders 67
Figure 54. The acoustic map of SEL noise exposition levels (dB re 1 μPa^{2}s) generated by single strikes of pile drivers in three locations (2 neighbouring and one at the distance of 20 km) as affecting fish with swim bladders..... 68
Figure 55. The maximum ranges of the noise impact on seals from pile driving conducted simultaneously in two places in the Baltica, BŚII and BŚIII OWFs (PW-weighted SEL)..... 70
Figure 56. The maximum ranges of the noise impact on the harbour porpoise from pile driving conducted simultaneously in two places in the Baltica, BŚII and BŚIII OWFs (HF-weighted SEL)..... 71
Figure 57. The maximum ranges of the noise impact on fish with swim bladders from pile driving conducted simultaneously in two places in the Baltica, BŚII and BŚIII OWFs (unweighted SEL)..... 72

Figure 58. The maximum ranges of the noise impact on fish without swim bladders from pile driving conducted simultaneously in two places in the Baltica, BŚII and BŚIII OWFs (unweighted SEL) 73