Near Real-Time Underwater Sound Modeling of Dredging Noise to Meet Regulatory Noise Thresholds

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Abstract

The Fehmarnbelt Fixed Link consists of an immersed tunnel connecting Denmark and Germany in the western Baltic Sea. Marine sediments are excavated to create the tunnel trench. The importance of the Fehmarnbelt for the harbor porpoise is

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recognized and managed in German waters through a Natura 2000 area. The authorities defined two indicators to safeguard its function. The first threshold demands that not more than 20% of the cross-section between Lolland and Fehmarn shall be exposed to construction Sound Pressure Level exceeding 144 dB ref. 1 μPa. The second threshold states that not more than 1% of the Natura 2000 area shall be exposed to construction Sound Pressure Level exceeding 140 dB ref. 1 μPa from June to September.

Measurement of dredging sound does not allow to assess the compliance with these thresholds since public shipping sound regularly exceeds them already. Therefore, a hybrid approach combining real-time modeling and continuous measurements has been developed, using measurements for continuous calibration of the model.

Results of the first and half construction year revealed an average deviation between the model and measurements less than 1 dB. Compliance with the thresholds is assessed with confidence and reliability despite the interference of sounds introduced by other maritime activities.

Keywords

Sound map · Noise map · Modeling · Calibration · Threshold · Dredging · Harbor porpoises · Compliance

Introduction

Anthropogenic underwater noise is recognized as a threat to marine wildlife, and there are growing needs to monitor, mitigate, and regulate it. Underwater noise may be harmful to cetaceans through interfering with their acoustic communication, orientation, and prey capturing abilities and – at high doses – might even lead to auditory damage. While much knowledge has accumulated about the responses of marine mammals to impulsive sounds from offshore pile driving or seismic surveys (Richardson et al. 1995; Southall et al. 2007; National Marine Fisheries Service 2018), much less is known about their reaction to continuous sound from shipping or dredging (McQueen et al. 2020). Although ships are not the loudest sources of underwater noise, their sheer abundance makes shipping sound a very important source of chronical anthropogenic noise in the oceans (Hildebrand 2009; OSPAR Commission 2009). Ambient noise levels have been rising in some regions along with an increase in shipping activity (Anderson et al. 2008; Andrew et al. 2011; Miksis-Olds et al. 2013; Kaplan and Solomon 2016). In the context of overall rising underwater noise levels, also dredging noise receives growing attention and the Central Dredging Association also addressed the issue (CEDA 2011). CEDA acknowledged that dredging involves a variety of activities, which produce underwater sounds but also concluded that appropriate management practices lack standardized monitoring protocols. Dredging sound is diverse but usually only of moderate intensity except for Trailing Suction Hopper Dredgers, which emit relatively high underwater noise levels (Robinson et al. 2011). As dredging operations may include a variety of vessels, an assessment of underwater sound cannot simply focus on the dredgers but must assess the whole operation.

The construction of the Fehmarnbelt Fixed Link as an immersed tunnel involves extensive dredging operations for an extensive period of time and space. The Fehmarnbelt Fixed Link will consist of a 17.6 km long, immersed tunnel connecting the Danish Island of Lolland and the German island of Fehmarn in the western Baltic Sea (Fig. 1). For the first time in Germany, the relevant authorities have imposed restrictions to underwater sound from dredging and associated activities to preserve

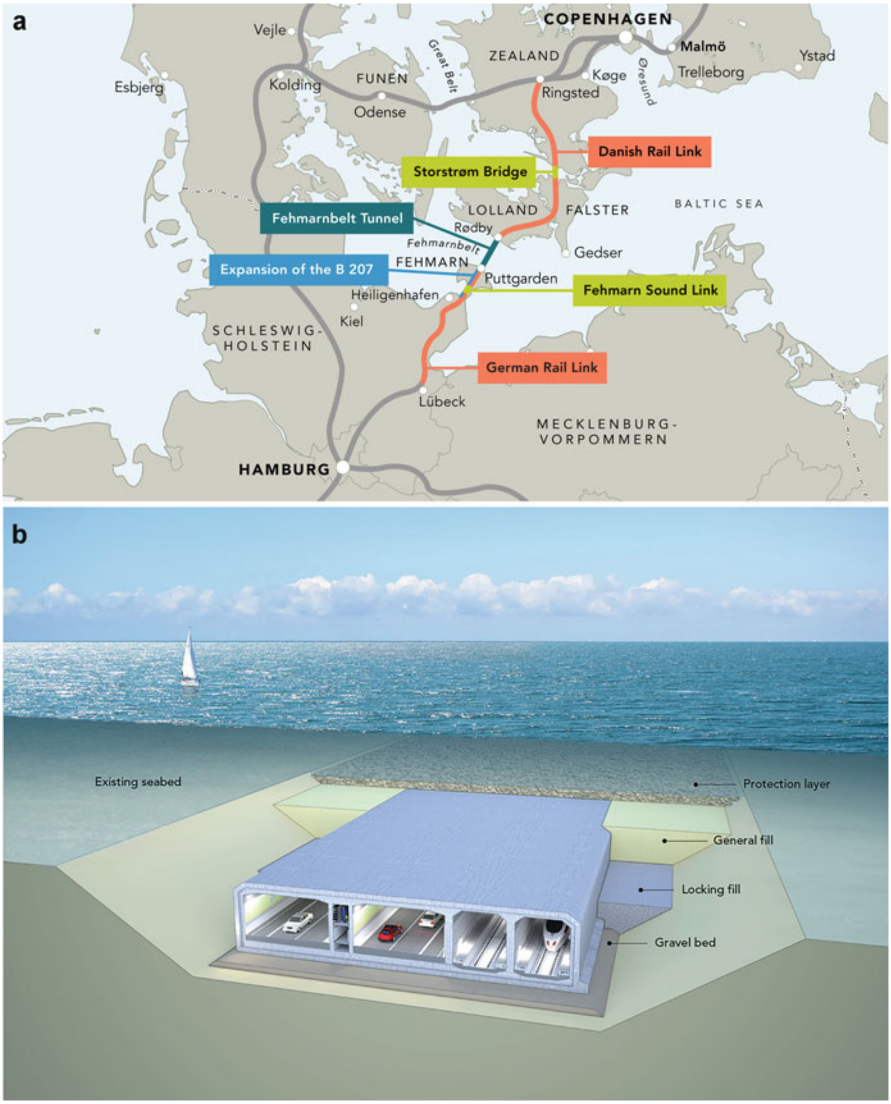

Fig. 1 The Fehmarnbelt tunnel project. (Copyright: Femern A/S)

the habitat of the population of 2000–4000 harbor porpoises staging and nursing in the Fehmarnbelt (FEMM 2013). These restrictions induce an obligation to monitor, manage, and limit the overall sound levels according to requirements defined in the plan approval decision. The first restriction demands that not more than 20% of the cross-section between Lolland and Fehmarn shall be exposed to construction Sound Pressure Level exceeding 144 dB ref. 1 μPa. The second restriction states that not more than 1% of the Natura 2000 area shall be exposed to construction Sound Pressure Level exceeding 140 dB ref. 1 μPa from June to September.

In this study, we outline a hybrid approach that combines continuous sound modeling and in situ underwater sound measurements as the most suitable and robust method for assessing the compliance with regulatory metrics. The continuous assessment of the compliance with two sound thresholds defined by the regulatory authorities is described and the uncertainties assessed.

The Sound Exposure Issue Related to the Tunnel Construction

Activities Involved in the Tunnel Construction

For the construction of the tunnel, marine sediments need to be excavated to create a tunnel trench about 90 m width and 16 m depth for the subsequent immersion of the tunnel segments. The construction includes extensive dredging operations. The dredging will result in around 19 million cubic meters of sand, stone, and soil.

Different types of dredging vessels conduct the dredging operation at sea (Fig. 2). In the coastal areas, backhoe dredgers are deployed. Further offshore, in deeper waters so-called grab dredgers and trailing suction hopper dredgers are used. In total, more than 100 vessels have been involved 24 h per day during the first and half year of construction, including Trailing Suction Hopper Dredgers, Backhoe Dredgers, Grab Dredgers, Tugs, Barges, Survey vessels, etc.

Sound Exposure for Harbor Porpoises

The Fehmarnbelt is a natural habitat of the harbor porpoise (*Phocoena phocoena*), a small odontocete whale which is the only cetacean species regularly reproducing in

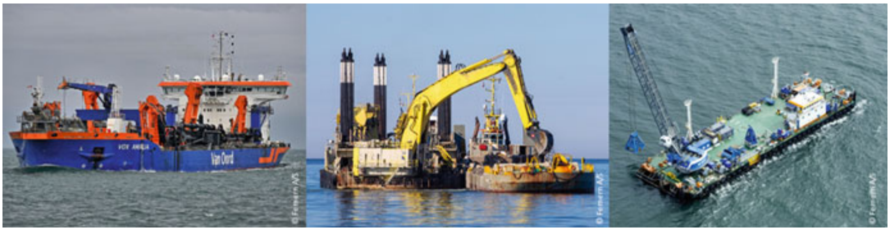

Fig. 2 Example of different dredgers involved in the tunnel construction. (Copyright: Femern A/S)

the Baltic Sea. Harbor porpoises of the Fehmarnbelt belong to the population of the western Baltic Sea which comprises about 20,000–40,000 individuals. The wider Fehmarnbelt area has a function as a staging and nursing area for 2000–4000 individuals with highest numbers during spring and early summer (FEMM 2013). During spring and autumn, porpoises are migrating through the Fehmarnbelt which is the main connection between the Danish Belt Sea and the Baltic Proper. In the center of the Fehmarnbelt, a marine protected area as part of the European Natura 2000 network has been established in 2007 to protect harbor porpoises.

As harbor porpoises show aversive responses to underwater sound, it has been extensively discussed with German authorities and NGOs whether the construction of the tunnel may negatively affect the function of the Fehmarnbelt for this species. The environmental impact assessment concluded that porpoises are less sensitive to continuous noise and that the construction of the tunnel will not impair harbor porpoise population in the Fehmarnbelt (Femern A/S and LBV SH 2013).

Sound Indicators and Thresholds to Prevent Impacts

For the first time in Germany, the relevant authorities have imposed restrictions to underwater noise from dredging and shipping as well as a demand to monitor and manage noise according to the following requirements:

1. Not more than 20% of the cross-section between Lolland and Fehmarn shall be exposed to construction Sound Pressure Level exceeding 144 dB ref. 1 μPa to avoid creating a barrier effect that may impede porpoise migration (indicator 1).
2. Not more than 1% of the protected Natura 2000 area shall be exposed to construction Sound Pressure Level exceeding 140 dB ref. 1 μPa during the reproductive period of harbor porpoises from June to September to minimize the impact on the protected area and on reproducing porpoises (indicator 2).
3. The compliance to these thresholds shall be monitored continuously as part of the environmental construction monitoring.

The Hybrid Model-Measurement Approach

The Maritime Context of the Fehmarnbelt

The Fehmarnbelt is a strait connecting the Bay of Kiel and the Bay of Mecklenburg in the western part of the Baltic Sea between the German island of Fehmarn and the Danish Island of Lolland (Fig. 3). Ferries connect Puttgarden and Rødby on the two islands. The strait features a 10 nautical miles wide area with depths of 20–30 meters. Currents in the strait are weak and mostly dependent on wind.

The Fehmarnbelt is one of the busiest waterways in Europe. Figure 4 is representing the cumulative time when the ambient sound exceeded 140 dB ref. 1μPa (dominance map) before the project activities in the marine environment

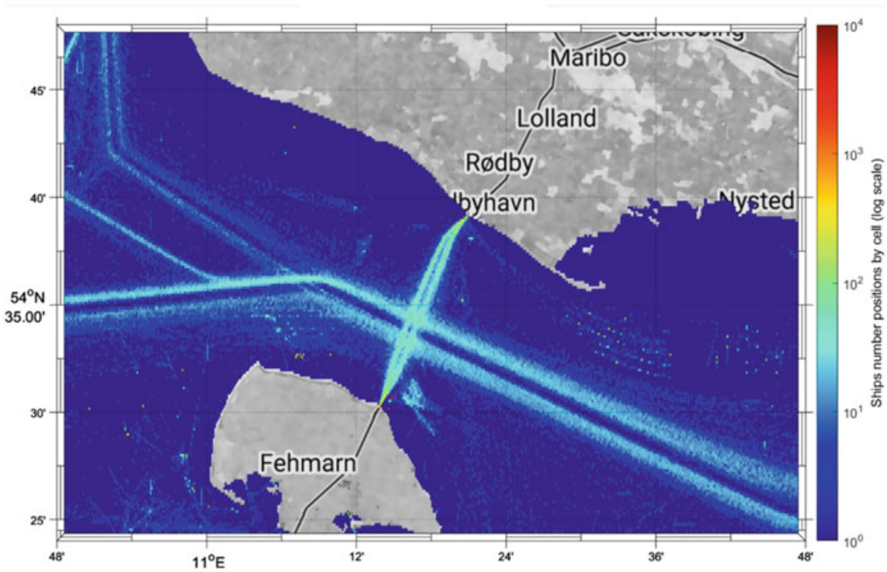

Fig. 3 Maritime traffic density map in the Fehmarnbelt before the tunnel construction started in 2020

started. This dominance map shows that the sound of the shipping route connecting the North Sea and the Baltic Sea and the ferry line between Germany and Denmark cause levels of ambient sound pressure levels that may overcast construction sounds above 140 dB ref. 1μPa up to about 10% of the time (Fig. 4).

The Model-Measurement Hybrid Approach

Since the commercial shipping and the ferry vessels generate sounds that already regularly exceed 140 dB ref. 1μPa and 144 dB ref.1 μ Pa, monitoring construction sounds in the Fehmarnbelt, the monitoring of construction sound and compliance with the thresholds, i.e., the two noise indicators, cannot be achieved by sound measurements alone. Indeed, direct measurement of the sound in the Fehmarnbelt would include sounds from all sources, commercial shipping, ferry vessels, etc., mixed with the sounds of the tunnel construction activities. The analysis of measured only values it would not be conclusive whether any excess of the thresholds is originated from the construction activities or from the other vessels. By nature, the sound measurement records all sounds, and it is not possible to separate contributions from the construction with sounds from the overall traffic. In addition, the spatial nature of the indicators, calculated along the cross-section and into the Natura 2000 area, cannot be assessed with only hydrophones.

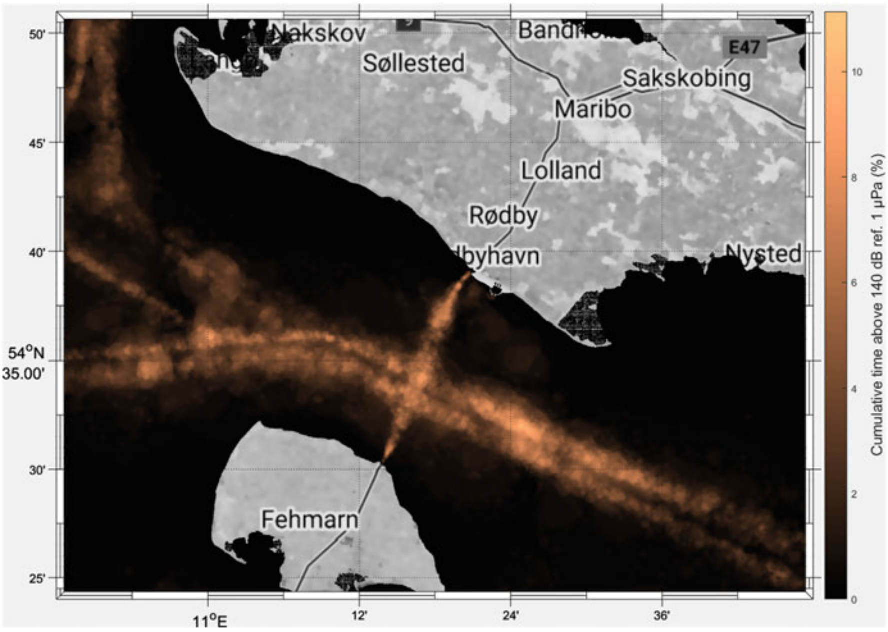

Fig. 4 Proportion of time when the shipping sound exceeding 140 dB ref. 1 μPa before any tunnel trench dredging started in 2020

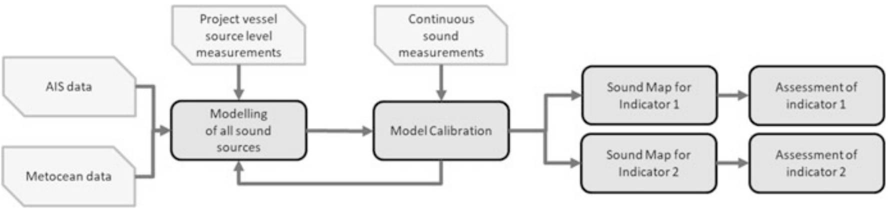

Fig. 5 Overview of the hybrid methodology to model, calibrate, and assess both regulatory indicators

A method to handle this intrinsic characteristic of the measured data for model calibration has been developed and is detailed hereafter. The construction sound monitoring follows a hybrid approach which enables the cumulative sound from construction activities and the ambient sound from the usual maritime traffic being assessed separately. The hybrid nature of the approach is combining near real-time modeling, continuous sound measurements along the construction sites, and dedicated measurements of underwater radiated noise (URN) of most of the vessels involved in the project (Fig. 5).

Sound Measurement Strategy

A dedicated protocol has been defined to perform the sound measurements in order to ensure that the data would be suitable for the implementation of the hybrid approach.

Three categories of measurement have been defined: category A consists of the measurement of the source levels (underwater radiated noise – URN) of the vessels involved in the construction. Category B consists of measurements at the vicinity of the construction site. Category C consists of long-term measurement at a distance from the construction areas.

Category A measurements are dedicated to the source-level measurements of various construction vessels involved in the tunnel construction. Levels are measured individually or representatively per vessel type. The processing of the URN takes into account the environmental conditions of the measurement site (such as sediment grain size) and the configuration of the measurement (such as the range between the hydrophone and the vessel). Source levels are estimated for different representative activities such as dredging and disposal by backhoe dredger (BHD), grab dredger (GD), and trailing suction hopper dredger (TSHD), steaming, anchoring, etc., including also tugs and service vessels operating under various activities. The source levels obtained, which includes the measurement of the source directivity, are integrated in the sound model.

Underwater sound is also continuously measured along the offshore working sites and used to validate and continuously recalibrate the model. Four mobile underwater sound measuring devices (Fig. 6) per offshore working site are deployed within a few hundred meters of the construction-related work. These mobile measuring

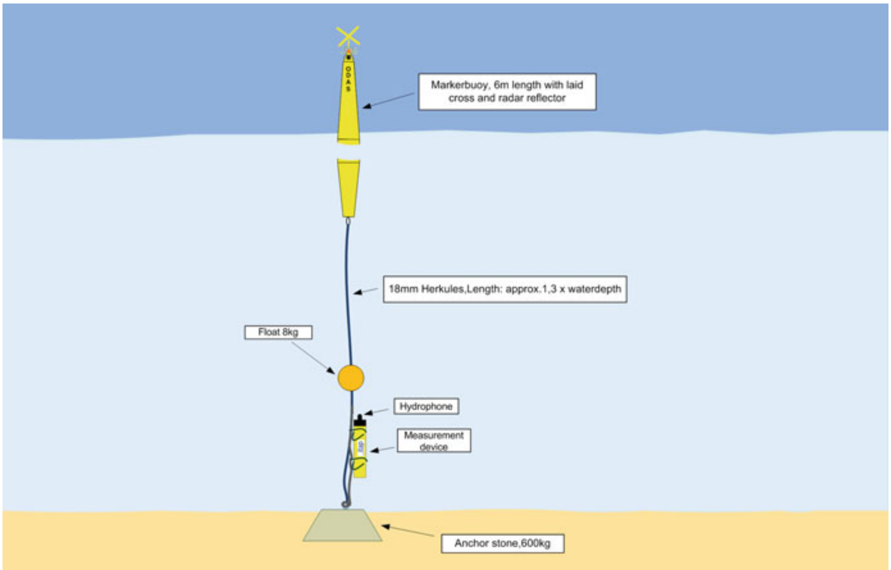

Fig. 6 Sketch of the acoustic moorings

devices are maintained weekly, i.e., the position is adjusted according to the construction progress and the measuring data are retrieved for subsequent data analysis.

In addition to the mobile underwater noise measuring devices in the near field of the offshore working areas, two permanent measuring stations are deployed at some distance to the construction areas (Fig. 7). These monitoring positions are maintained bimonthly.

For the mobile and the fixed measuring stations, standardized underwater noise measuring recorders are used that meet all requirements of the measuring regulations for underwater sound measurements (BSH 2011) (Verfuß et al. 2015) and are also calibrated regularly. The measurements are performed continuously with a sampling rate of at least 48 kHz so that the frequency range between 20 Hz and 20 kHz is covered. Measured sound pressure levels are processed into 20-s windows data in 1/3-octaves.

Noise measurement devices measure the entire total noise including natural noise from waves, splashes, and rain as well as other shipping sounds than that originating from construction activities. Sound measurements thus do not allow a direct assessment of construction sound. Therefore, the recorded underwater sound measurements.

Sound Modeling

Sounds are modeled with the web-based Quonops© Online Services modeling platform (Folegot 2009, 2011). Although Quonops© supports other modeling

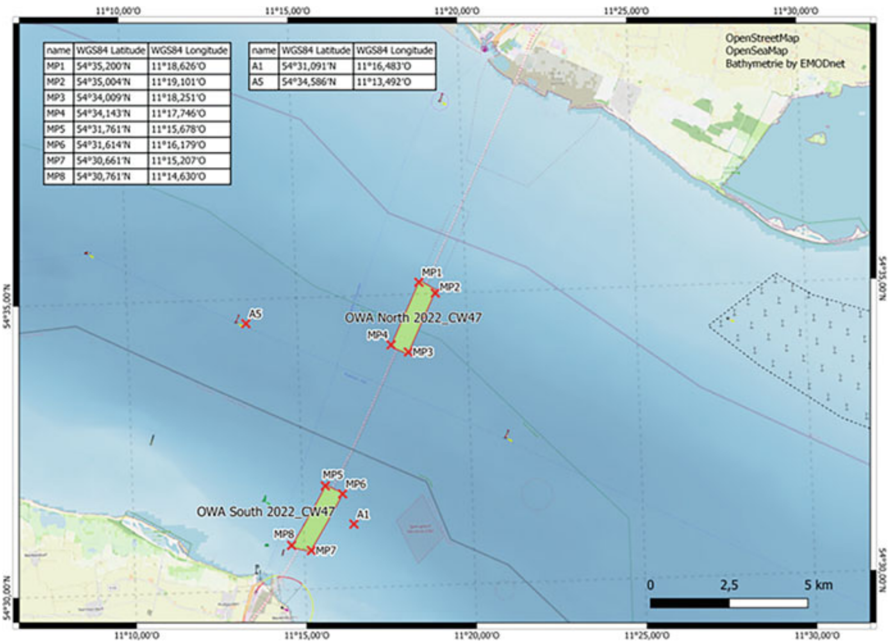

Fig. 7 Example of the design of the sound measurements done in the construction sites and the long-term measurements at a distance of the construction activities

techniques, in the framework of this project, Quonops© is solving the sound propagation Helmholtz equation by using the parabolic equation approximation parabolic modeling (Collins 1994; Collins et al. 1996). Broadband modeling is done in 1/3 octave bands from 16 Hz to 4 kHz for each sound source independently. Automated Identification System (AIS) data provides the near real-time position of all vessels continuously. Project vessel and related activity sounds are derived from the category A measurements, while the source levels from the non-project vessels are estimated from vessel size and sailing speed based on the RANDI 3 model (Wagstaff 1973; Ross 1976; Breeding et al. 1996).

The modeling of sound propagation is done for each sound source by a series of cylindrical vertical planes (Nx2D technique) with azimuths around the sound source spaced by 3°.

The oceanographic context is considered in the modeling: the sound speed profiles in water are derived from water temperature, salinity, and pressure (or depth) provided by operational oceanographic services and updated every hour. The main effect of these non-homogeneities in sound speed distributions is to create propagation channels. These complex phenomena are, however, predictable by numerical simulation.

The sediment properties and the changes of the bathymetry of the marine environment are also taken into consideration in the resolution of the Helmholtz Equation by considering the propagation in the marine substrate and the reflections from the water-sediment interface. These characteristics of the marine environment induce absorption, reflection, and diffusion of the sound through the soil and in the water column. The descriptive data of the bottom and bathymetry are taken from available local data.

The model calculates the sound originating from natural sources derived from the wind field data (Ainslie 2010) and all non-construction vessels – which in combination equates the so-called background noise – and construction vessels separately.

The model predicts the project vessel-based cumulative sound by integrating the individual source levels measured for the vessels involved in the construction activities and their near real-time positions provided by the AIS stream. This provides modeling of the background sound (i.e., the sum of all non-project-related sounds) and project-related sounds in near real time, separately as well as combined to form the total sound field (Fig. 8).

This approach allows for calibration of the model from cumulative sound levels recorded from non-project and project sounds, on the one hand, and the assessment of both conditions to verify compliance every 15 min, 24/7, on the other hand.

Model Calibration

The hybrid approach combines near real-time modeling provided by the Quonops© Online Services platform and the sound measurements. The modeling results are validated by recurring category B and C underwater noise measurements during the construction activities, allowing the model to be recalibrated periodically with the most recent underwater noise measurements. This procedure ensures that the model provides the best estimate of the overall sound at each measurement position.

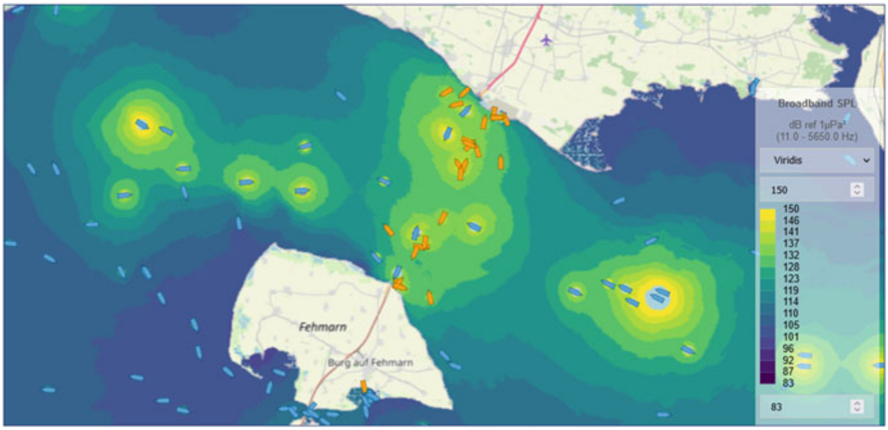

Fig. 8 Instantaneous total sound map. Project and non-project vessels are displayed in orange and blue, respectively

The comparison of measured and modeled data is based on the total sound composed of construction sounds and background sounds. However, neither a detailed analysis of different situations for different time periods of the recordings nor a complex individual consideration of individual activities is possible.

The calibration methodology has been initially developed during the BIAS project (Folegot et al. 2016). The Cumulative Density Function (CDF) is used to overcome the difficulty that the measurement and the modeling are not performed at similar time resolutions by defining a common robust metric. The CDF describes the statistical content of the sound for the period considered similarly for both the measurement and the modeling, regardless of the technical characteristics of the measurement or the modeling. The CDF expresses the relationship between the sound level and the percentile, e.g., the proportion of time a given level occurs.

The calibration process consists of finding the best set of model parameters that minimize the difference between the CDF provided by the measurement and the CDF provided by the model at the position of the measurement and for the same period. The calibration is performed by minimizing the differences between both measured and modeled CDF by considering the following uncertainties:

- Wind: the wind fields are converted into sound of natural origin. The measurement provides a ground truth of natural noise and help to consider the local conditions that influence the natural noise generated by wind.
- Sediment: it is acknowledged that uncertainties in the description of the soil parameters need to be addressed. Therefore, we use a calibration process that will enable to model to decide on a set of geo-acoustic parameters that make the model fit best the natural noise component of the measurements.
- Non-project source levels: it is acknowledged that the diversity of commercial vessel designs, propellers, sizes, and hulls introduce uncertainties in the

estimation of the source levels of the vessels. The RANDI 3 source-level model provides an a priori assessment. The calibration process accounts for this uncertainty and uses the measured ambient noise levels to adjust the source levels of the non-project vessels.

The assessment of the quality of the calibration is quantified by the calculation of the root mean square of the absolute difference between both measured and modeled CDF between the 5th and 95th percentiles (Fig. 9, left) and is updated on a weekly basis for all available measurement positions. From the start of the dredging in July 2021 to April 2022, more than 300 calibrations have been performed and the model-measurement mismatch has never exceeded 2 dB and is usually around 0.7 dB (Fig. 9, right).

Model Validation

To validate the model, the modeling of the total sound (project and non-project activities in the Fehmarnbelt) is regularly compared with the acoustic measurement. An illustration of the comparison is provided in Fig. 10. The figure reveals a good agreement between the model and the sound measurements. It is important to note that there is a discrepancy between the continuous measurements of the total sound that are processed in 20-s windows and averaged on 15-min windows (black lines). The model on the other side provides a snapshot every 15 min (blue dots for the total sound, orange dots for the sound not related to the project activities). The gray area in the background explicit the variability of the measurement between the 1st and 99th percentiles. There is a good agreement between the total sound levels modeled (in blue) that are close to the higher percentiles of the measurements. On the other hand, the modeled background levels not related to the construction activities are minimizing the lowest percentile measured. This is an expected result which highlights that the total sound is a mixture of construction and non-project sounds that cannot be reported by the measurement.

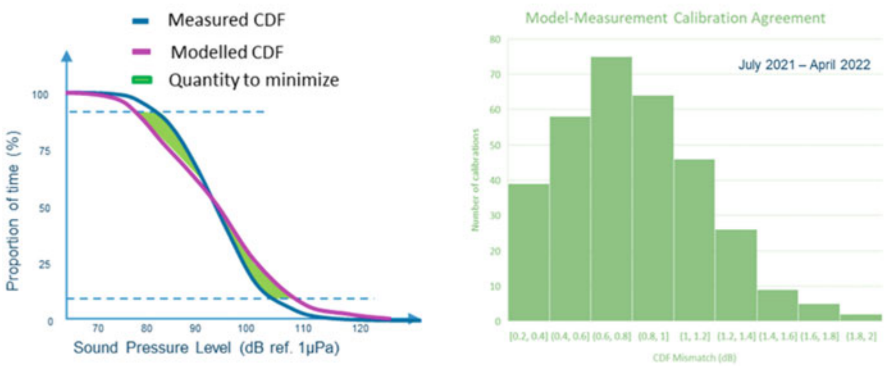

Fig. 9 Left: The calibration of the sound modeling is based on the minimization of the difference between the measured and modeled Cumulative Density Functions (CDFs). Right: Distribution of the model-measurement statistical mismatch from July 2021 to April 2022

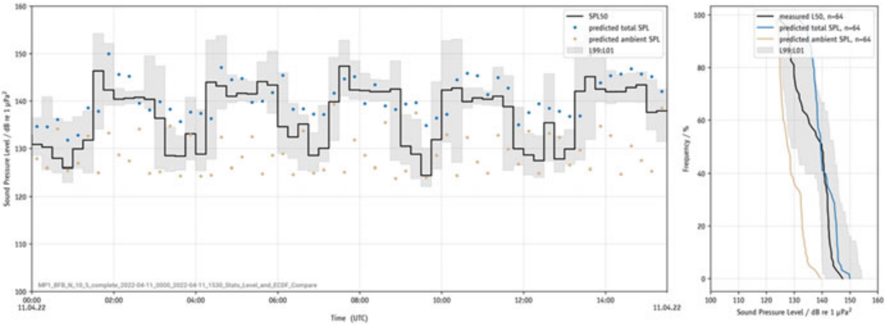

Fig. 10 Course of the modeled and measured sound levels in April 11, 2022, at the measuring station MP1. The sound pressure level data are processed in 20-s windows and then averaged in 15-min windows (black line). The blue and brown dots represent the total and background sound, respectively, as predicted by the model. The gray background represents the 1–99% excess level of the measured values for the 15-min averaging intervals. The figure on the right is the Cumulative Function representation of the data

Compliance with the Noise Indicators

Indicator 1: Prevent a Barrier Effect

Indicator 1 attempts to represent the blocking effect potentially induced by the noise of the project on the passage of underwater fauna in the Fehmarnbelt channel. It is assumed that this effect becomes significant when more than 20% of the cross-section between Lolland and Fehmarn is exposed to sound levels above 144 dB ref. 1 µPa at all times.

To assess indicator 1, only the project's stationary activities near the site of the future tunnel are taken into account: this concerns project vessels sailing at speeds less than 3 knots (limit for considering vessels engaged in noisy dredging, towing, unloading, etc.) and which are located less than 300 meters from the cross-section (imaginary line of 17.6 km between Germany and Denmark, drawn at the location of the future tunnel) (Fig. 11).

The cumulative noise of these activities is calculated by the Quonops model every 15 min (Fig. 12), and their sound footprint beyond 144 dB ref. 1µPa is projected on the cross-section: the value of the indicator is given by the proportion of cross-section subject to a sound level greater than 144 dB ref. 1µPa compared to the total length of the cross-section.

The project shall not exceed the 20% limit imposed on indicator 1: this means that the noise generated at the construction site beyond 144 dB ref. 1µPa must not occupy more than 3.6 km (cumulative length) of the width of the channel between Germany and Denmark.

Figure 13 shows the evolution of the values for indicator 1 from December 2021 to July 2022. The fluctuations give a history of the project: highest values testify the

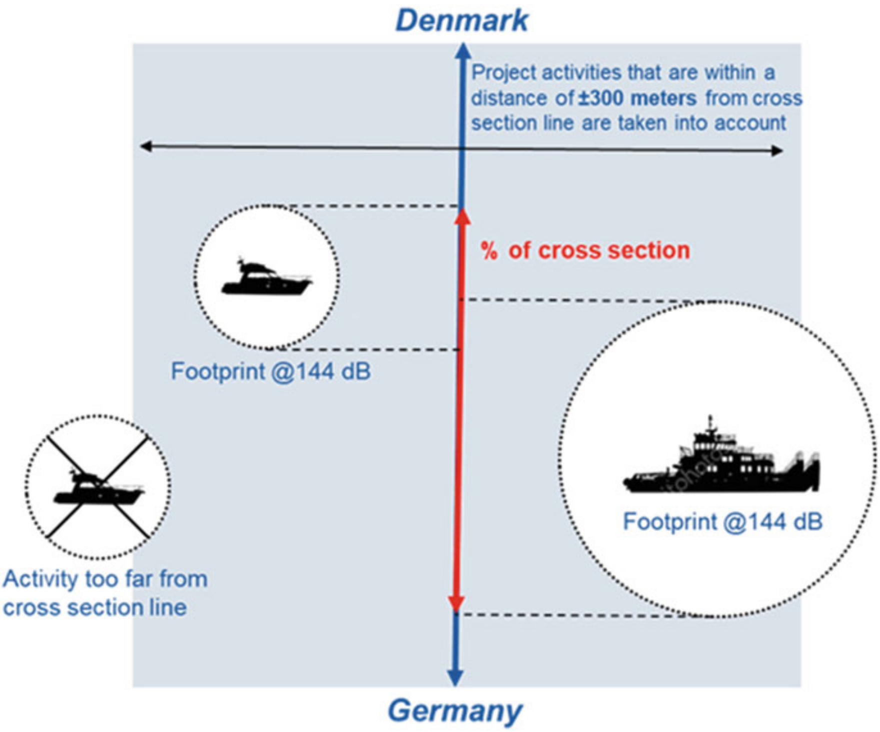

Fig. 11 Overview of the methodology to assess indicator 1

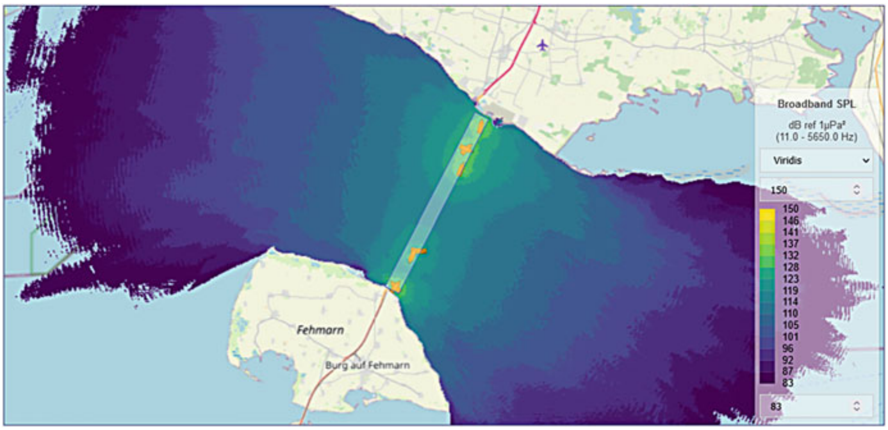

Fig. 12 Example of sound map used for the calculation of indicator 1

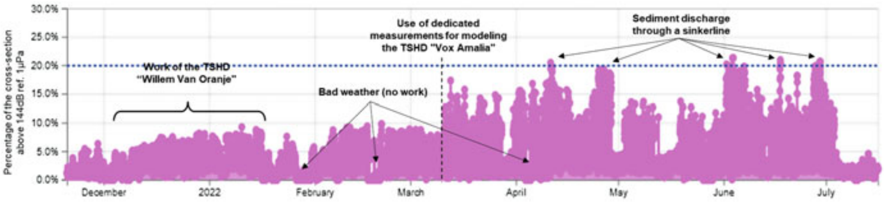

Fig. 13 Percentage of the cross-section of the Fehmarnbelt above 144 dB ref. 1μPa (indicator 1)

local dominance of sound from project activities along the cross-section. More specifically, the Trailing Suction Hopper Dredgers such as “Willem Van Oranje” and “Vox Amalia” are among the loudest project vessels and contribute significantly to the values of indicator 1. The lowest values of indicator 1 can be attributed to periods of bad weather which caused the work to stop and in fact the emission of noise by the project in the channel Fehmarnbelt.

Following the use of dedicated measurements of the TSHD “Vox Amalia” in the modeling, the values of indicator 1 increased significantly from the end of March 2022. In April and June, the values briefly exceeded the 20% threshold, during the discharge of sediments by the TSHD into a sinkerline, the blocking effect of which is taken into account by the model. In such situations an investigation is performed, and a solution shall be found to reduce the noise level.

Indicator 2: Limit Sound in the Marine Protected Area

For indicator 2 (1% of the Natura 2000 site), all construction vessels, irrespective of their speed and position, are considered by determining the construction-related noise levels. The project site intersects a Natura 2000 marine area where porpoises are protected during their summer breeding period (from the beginning of June to the end of September). Indicator 2 attempts to represent the proportion of this protected area exposed to loud project noise set to 140 dB ref. 1μPa by the authorities.

The cumulative sound of these activities (Fig. 14) is calculated by the Quonops model, and the value of indicator 2 is defined by the proportion of the marine protected area exposed to sound levels higher than 140 dB ref. 1μPa, compared to its total surface (280 km^2) (Fig. 15).

The project shall not exceed the 1% limit imposed on indicator 2 from June to September: this means that the noise generated by the construction site beyond 140 dB ref. 1μPa must not occupy more than 2.8 km^2 of the surface of the Natura 2000 marine protected area during this time of the year. Outside this period, the limit is raised to 10%.

Figure 16 shows the evolution of indicator 2 between December 2021 and July 2022. Similar to indicator 1, the fluctuations of indicator 2 can be attributed to particular events in the construction project: some high and isolated values correspond to occasional passages of project vessels crossing the Natura 2000 protected area, while the lower values correspond to localized works in the area or in the

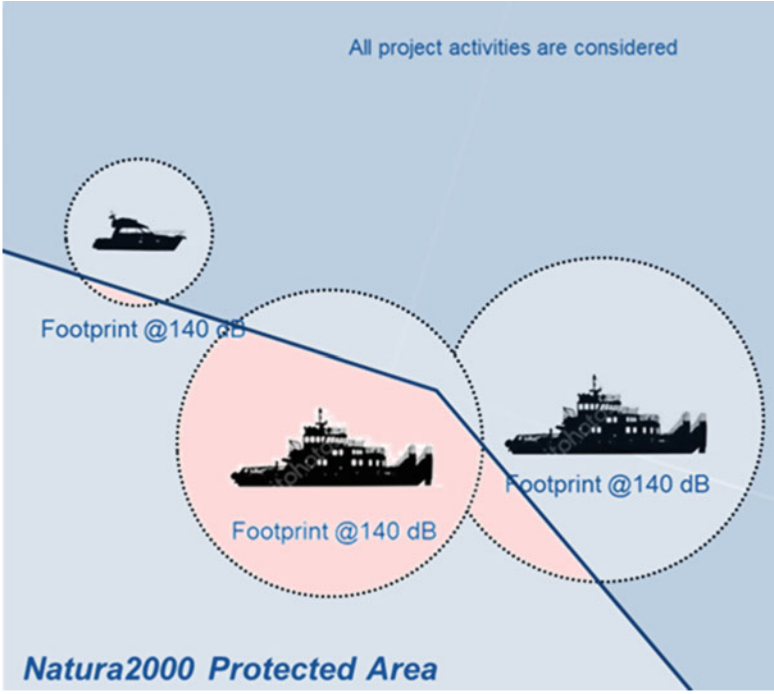

Fig. 14 Example of sound maps used for the calculation of indicator 2

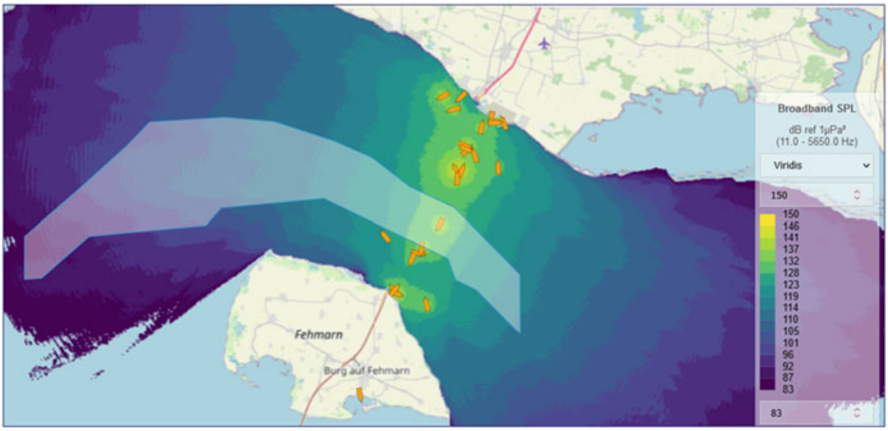

Fig. 15 Overview of the methodology to assess indicator 2

vicinity of the area. Outside the porpoise reproductive season in summer, the threshold for indicator 2 may not exceed 10%. However, from June to September, the threshold is 1%: the active management of the project has led to a reduction of vessel activities from the first of June 2022 to comply with the threshold.

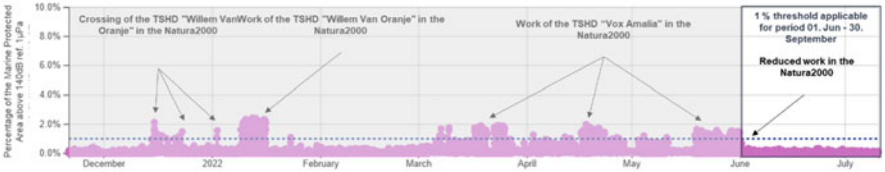

Fig. 16 Percentage of the Natura 2000 area above 140 dB ref. 1μPa (indicator 2)

Conclusion

The regulatory thresholds defined to protect the marine environment from the sound generated by the construction project of the tunnel across the Fehmarnbelt aim at preventing a barrier effect and maintaining a quality of the habitat in the Natura 2000 area “Fehmarnbelt”.

The busy maritime context of the Fehmarnbelt generates a large amount of ambient sound that may overcast construction sounds more than 10% of the time. Therefore, a hybrid approach that combines in situ measurement with modeling was therefore mandatory to enable the assessment of the sound originated from the construction independently from the sounds of all other human activities. The method developed has led to an operational solution, providing near real-time monitoring of the regulatory thresholds continuously every 15 min.

The results of the first year and half year of real-time modeling and measuring underwater noise of the dredging work revealed a good fit of modeled underwater noise with the measurements. Therefore, project-related sound across the Fehmarnbelt can be predicted confidently and with sufficient accuracy to assess compliance with the regulatory thresholds for underwater sound despite the interference with the sounds introduced by the heavy commercial traffic.

Although the real-time assessment is fully automatized, it proved to be essential to have precise knowledge of the construction activities and the specifications of the construction vessels and their source levels. Though source levels can be calculated from available sources, it is recommended to measure source levels of specific activities at the construction sites to reduce the uncertainties of the model as much as possible.

Underwater noise modeling was accompanied by extensive noise measurements which allowed routine calibration of the model. The stability of the model has been achieved thanks to the numerous measurement stations.

The monitoring of the sound indicators is actively used by the project management to plan and organize the operations of the project. The compliance achieved since the start of the project has proven to be successful to protect the marine environment and the approach can be recommended to other projects where the occurrence of protected species may require managing underwater sound.

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