MANAGING DREDGING NOISE DURING THE CONSTRUCTION OF THE WORLD'S LONGEST IMMERSED TUNNEL IN THE FEHMARNBELT BETWEEN DENMARK AND GERMANY

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Abstract: Underwater noise immissions from construction vessels has been subject to intensive discussions in the planning phase of the Fehmarnbelt Fixed Link Project, because of a lack of national or international standards to measure and assess noise from shipping and dredging. The Fehmarnbelt - though one of the busiest waterways in Europe - holds important numbers of the protected harbor porpoise, and the Immersed Tunnel will cross a protected Natura 2000 area established for this endangered population. The German Plan Approval decision limits Project-related underwater noise (mostly vessel-based construction noise) to facilitate porpoise migration through the Fehmarnbelt and to limit disturbance in the Natura 2000 area. Furthermore, Project-related noise immissions must be monitored to meet strict thresholds throughout the construction phase. Monitoring Project-related underwater noise is challenging as the soundscape of the Fehmarnbelt is dominated by commercial shipping noise which usually exceeds noise emitted by the construction vessels of the Project. Therefore, underwater noise monitoring cannot be performed solely by measurements. The approach chosen is an underwater noise model supported by parallel underwater noise measurements. The real-time model predicts the natural background noise as well as vessel-based noise. Based on source levels assigned to vessels as well as the relevant parameters influencing sound propagation, the model calculates the sound spread by every vessel in the area based on their positions derived from AIS data. This allows modeling ambient noise (i.e., the sum of all non-Project-related noise) and Project-related sounds separately in real time. Sound immissions along the construction sites are continuously measured with hydrophones and the noise recordings are used to evaluate model predictions and to calibrate the model. In this paper, first experiences with this twin approach of modelling and measuring from the Fehmarnbelt construction site are outlined.

Key words: Dredging, monitoring, near real-time sound modelling, threshold, underwater noise

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1 INTRODUCTION

Anthropogenic underwater noise is increasingly regarded as pollution and a threat to marine wildlife and there are growing attempts 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 noise 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 noise from shipping or dredging (McQueen et al., 2020). Noise propagates well in water and the noise emissions of a vessel may exceed natural ambient noise levels at distances of several 10 km. Although ships are not the loudest sources of underwater noise, their sheer abundance makes shipping noise a very important source of chronical anthropogenic noise in the oceans (Hildebrand, 2009; OSPAR Commission, 2009; United Nations, 2018). 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 as early as a decade ago the Central Dredging Association addressed the issue (CEDA, 2011). CEDA acknowledged that dredging involves a variety of activities that produce underwater sounds but also concluded that appropriate management practices lack standardized monitoring protocols. Dredging noise 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 noise immissions cannot simply focus on the dredgers but must assess the whole operation. The construction of the Fehmarnbelt Fixed Link as an immersed Tunnel includes extensive dredging operations and for the first time in Germany, the relevant authorities have imposed restrictions to underwater noise immissions from dredging and shipping as well as a demand to monitor and manage noise immissions according to their requirements.

In this publication, we outline a combined approach of noise modelling and measurements addressing continuous noise monitoring and successfully enabling compliance with the conditions of the Plan Approval decision.

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. To construct the Tunnel about 14.5 million m^3 of marine sediments need to be excavated to create a Tunnel Trench about 90 m wide by 16 m deep for the placement of the Tunnel segments. 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 the Baltic Sea. It is strictly protected by European and national laws. Harbor porpoises of the Fehmarnbelt belong to the population of the western Baltic Sea which comprises about 20,000 to 40,000 individuals. The wider Fehmarnbelt area has a function as a staging and nursing area for 2,000 to 4,000 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 to protect harbor porpoises.

As harbor porpoises show aversive responses to underwater sound, it has been extensively discussed 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). This was acknowledged in the Plan Approval decision, but to account for uncertainties, the Approval was set under the following conditions to safeguard the function of the Fehmarnbelt for harbor porpoises:

1. Noise mitigation indicator no. 1: Not more than 20 % of the alignment between Lolland and Fehmarn shall be exposed to construction Sound Pressure Level (SPL) exceeding 144 dB ref. 1µPa (to avoid creating a barrier effect that may impede porpoise migration.
2. Noise mitigation indicator no. 2: Not more than 1 % of the protected Natura 2000 area shall be exposed to construction Sound Pressure Level (SPL) exceeding 140 dB ref. 1µPa during the reproductive period of harbor porpoises from June to September to minimize the impact on the protected area and on reproducing porpoises.
3. The compliance to these conditions shall be monitored continuously as part of the environmental construction monitoring.

2 ENVIRONMENTAL CONSTRUCTION MONITORING

2.1 General approach

Monitoring construction noise in the Fehmarnbelt is a challenging task because of a major shipping route between St. Petersburg and Kiel and a busy ferry line (between Rødbyhavn and Puttgarden) in the area (Fig. 1) which cause high levels of ambient sounds which even exceed the predicted construction noise. As a result of this, monitoring of construction noise and compliance with the conditions of the Plan Approval decision cannot be done by noise measurements alone. The environmental construction monitoring thus follows a dual approach with sound immissions from construction activities and ambient sound from other vessels being predicted separately by real-time modelling and confirmed by continuous noise measurements along the construction sites.

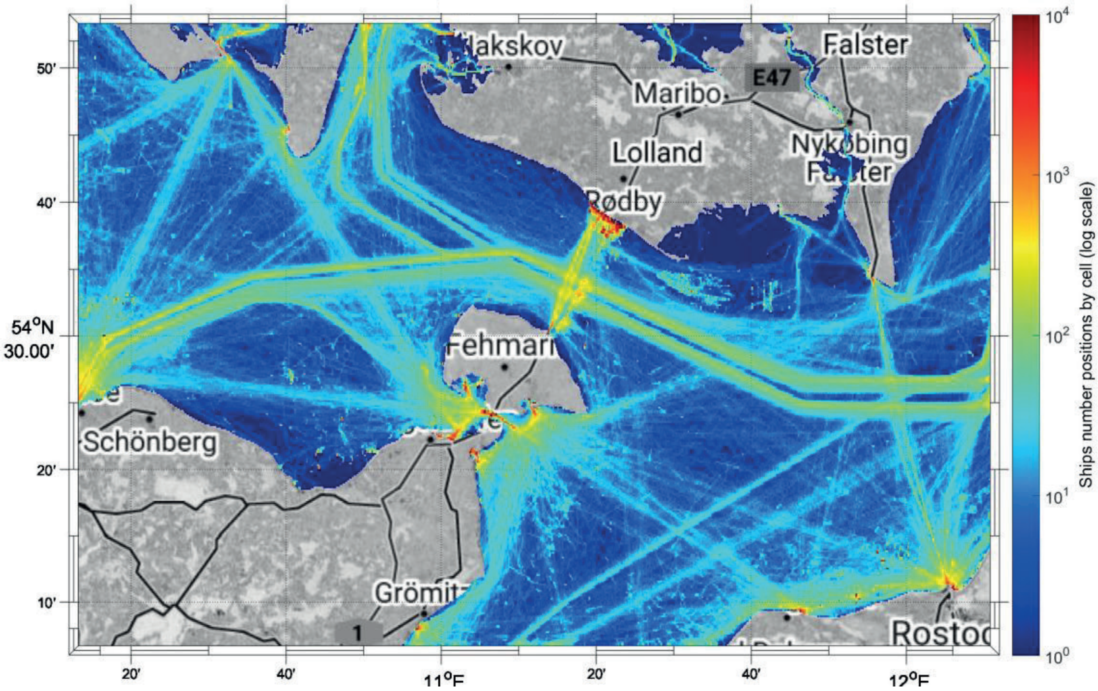

Figure 1. Maritime traffic accumulated over the month of June 2021

2.2 Underwater noise modelling

The assessment of construction-related noise immissions is achieved by consecutive modelling of the construction-related sound immissions continuously every 15 minutes around the clock and throughout the year as well as verifying the modelled noise maps with measurements. The modelling results are validated by recurring underwater noise measurements during the construction activities, allowing the model to be recalibrated periodically with the same underwater noise measurements. Since the measurements capture all sound sources, all vessels and vessel-based construction equipment such as dredgers are identified, tracked, and modelled based on their AIS signals in the Fehmarnbelt.

2.2.1 Model description

The sound immissions are calculated with the web-based Quonops© Online Services modeling platform (European Union Brevet n° EP2488839, 2009). This process allows for the separate assessment of construction-related sound immissions while calibrating the model by combining the measurements with the modelling of the overall noise. Quonops© is an underwater noise prediction platform built on the same philosophy as oceanographic or meteorological prediction systems (Folegot, 2011). Like oceanographic or meteorological forecasting systems, this platform produces an estimate of the spatio-temporal distribution of noise levels generated by all human activities at sea.

For continuous noise, the model output produced by Quonops© covers the needs as defined in existing and emerging national and international regulations regarding noise pollution levels and the preservation of habitats, marine ecosystems and the protection of marine species (Folegot and Clorennec, 2015). It offers additional knowledge of sound pollution through distribution mapping and enables the understanding of both the acoustic components of impact studies and the requirements of the Marine Strategy Framework Directive (MSFD) of the

European Union and of other regulations such as German and other noise thresholds. The platform is validated by more than 20,000 days of in-situ measurements carried out in various environments worldwide. Although several types of models solving the Helmholtz equation (Fig. 2) of wave propagation are embedded into the Quonops© platform, only the parabolic equation (Collins, 1994; Collins et al., 1996) is used for the Project which faithfully reflects the distribution of noise in the water column (Jensen et al., 2000). The exact position of all sound sources is used in their marine environmental context. Modelling is done at sub-wavelength scales for each source independently.

The sound speed profiles in water are three-dimensional and derived from water temperature, salinity, and pressure (or depth) provided by operational oceanographic services. The main effect of these non-homogeneities in sound speed distributions is to bend propagation rays and create propagation channels. These complex phenomena are, however, predictable by numerical simulation. The modelling of sound propagation is done by a series of cylindrical interpolated vertical planes (Nx2D technique) azimuths around the sound source spaced by 3°.

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 also calculating the propagation in the marine substrate (Fig. 2). These characteristics of the marine environment induce absorption, reflection, and diffusion of the sound through the bottom and in the water column. The descriptive data of the bottom and bathymetry are taken from available local data.

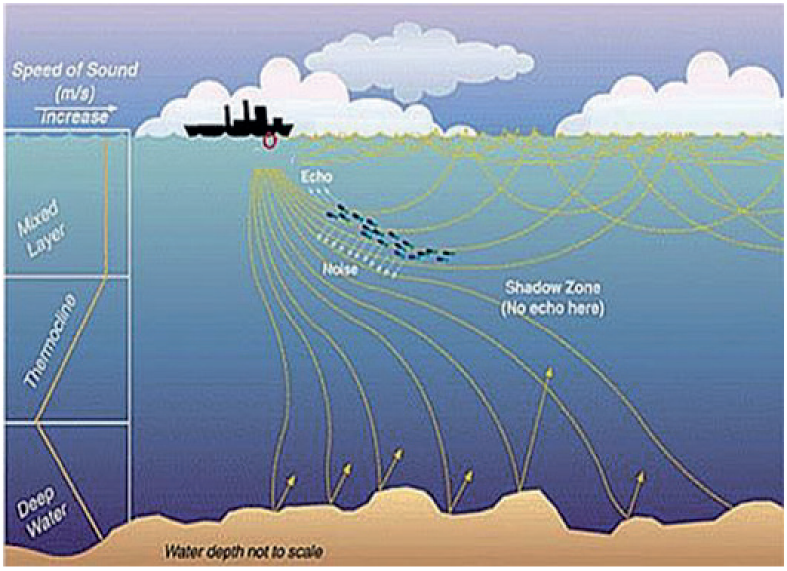

Figure 2. Modelling the propagation of noise in the water column in realistic oceanographic conditions. Image courtesy of the National Academy of Sciences

2.2.2 Model application

All construction vessels in the Tunnel Trench and up to 300 m east- and westwards with a speed of max 3 kts based on AIS tracks were considered for the calculation of construction related noise for the noise indicator no. 1 (20 % of the cross-section of the Fehmarnbelt). Therefore, the maximum source level approach per direction based on empirical data is used; irrespective whether this vessel is idle or in action, e.g. dredging. For indicator no. 2 (1 % of the Natura 2000 site “Fehmarnbelt”), all construction vessels were considered by determining the construction related noise levels. A comparison of the modelled construction noise levels with the overall measured noise close to the offshore working areas indicates that the model frequently overestimates the underwater noise conditions due to the assumptions used. This means the model output covers the worst-case scenario, maximizing the duration in which the loudest possible condition of the construction activities. Based on the modelled data, the areas exposed to noise levels of 140 dB ef. 1µPa or 144 dB ref. 1µPa are estimated.

Source levels of various construction vessels are measured while observing the prevailing environmental conditions (such as sediment grain size). The objective of the measurements is to collect noise levels of dredging equipment (incl. service vessels) and operations under various representative activities to be able to estimate source levels. For each of the vessel types, source levels of sound emissions are measured individually for different activities such as dredging, steaming, anchoring etc. Key operations are dredging and disposal by backhoe dredger (BHD), grab dredger (GD) and trailing suction hopper dredger (TSHD). All of these activities are supported by a fleet of tugs and work boats. Source levels of major noise producers are measured individually, whereas a sample of auxiliary activities are measured and considered representative for the multiplicity of activities of the same type.

2.3 Underwater noise measurements and model calibration

Underwater noise is continuously measured along the offshore working sites to validate and continuously recalibrate the model, resulting in a hybrid approach of modelling and measuring underwater noise (Fig. 3). Four mobile underwater sound measuring devices per offshore working site are deployed within a few hundred meters of the construction-related work (Fig. 4). These mobile measuring 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.

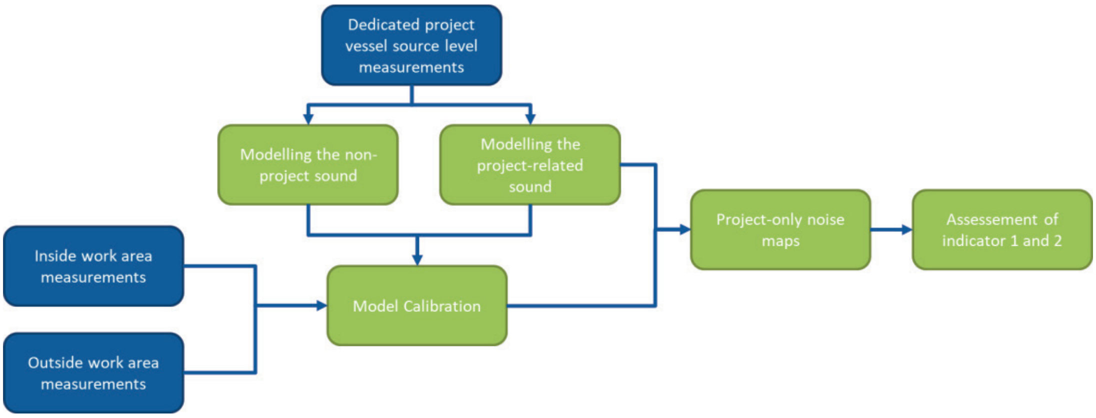

Figure 3. Schematic overview of the hybrid approach of measurement and modelling to achieve model calibration and assess both regulatory indicators

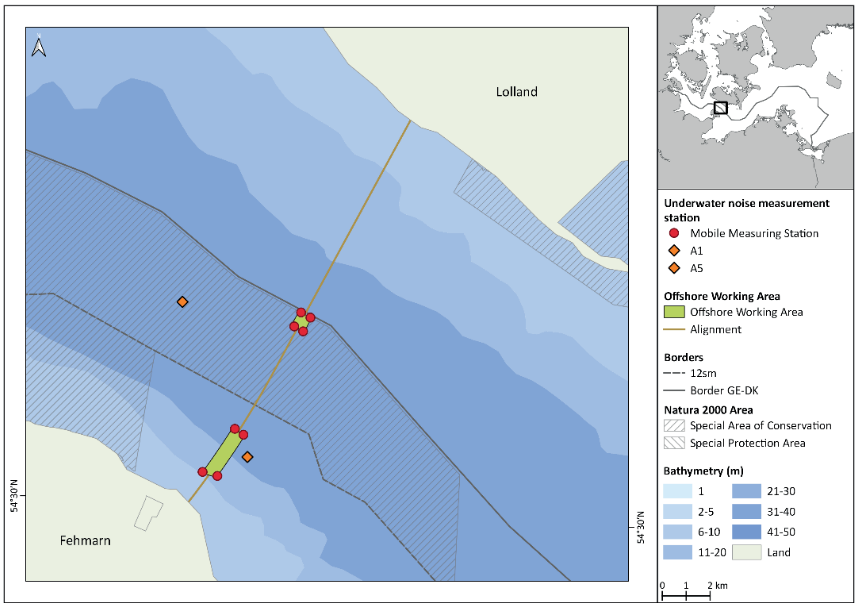

Figure 4. Locations of noise recorders at offshore working areas in the Fehmarnbelt

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. 4). 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) as well as ISO 18406 (2017) 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 will be covered. The variability of the source levels from the project vessels and its activities are corrected using the acoustic measurement and ensure that the model provides the closest estimate of the noise at the measurement position.

Noise measurement devices measure the entire total noise including natural noise from waves, splashes, and rain as well as other shipping noise than that originating from construction activities. Noise measurements thus do not allow a direct comparison of construction noise as predicted by the model. And the sole use of the measured underwater sound measurements cannot be applied for compliance with the noise thresholds defined in the plan approval that exclusively consider Project-related sounds. The model calculates the sound originating from natural sources and all non-construction vessels – which in combination equates the background noise – and construction vessels separately. The comparison of measured and modelled 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 will be possible. Instead, a standard procedure is developed for validating the model data with the measurement data, and the verification of the Quonops© model results is carried out continuously with the latest measurement data.

The comparison is made using the cumulative probability density function (CDF) of the modelled and measured Sound Pressure Level (SPL) for the same period of time, which is usually one week of measurements at sea in this Project (Fig. 5).

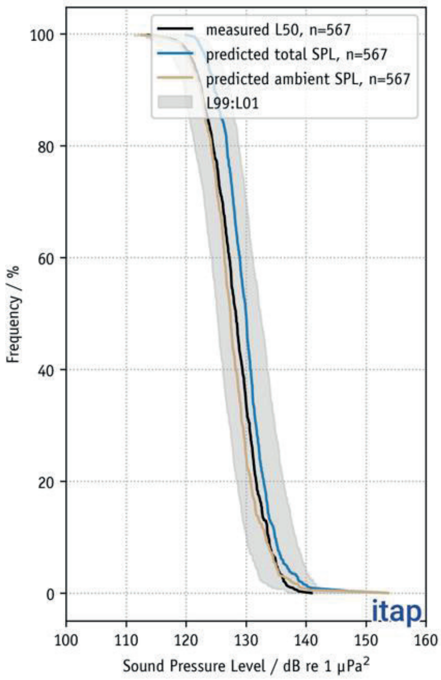

Figure 5. Cumulative Density Function comparison plot. Data originate from a single measurement position in close vicinity to an offshore working area and the modelled results of Quonops© model for the same location and time interval. L50 denotes the median of the measured sound pressure value (SPL), n is the number of observations used to create this plot (567 observations of 15-minute interval ~ one week of measurement). The gray shaded L99:L01 area denotes the range of the measurement values within the 1 % and 99 % exceedance levels.

3 FIRST RESULTS FROM CONSTRUCTION MONITORING 2021

Dredging of the Tunnel Trench started in July 2021. During the summer, dredging started in two offshore working areas using mostly two grab dredgers and two backhoe dredgers (Fig. 6). By the end of the year, an additional Trailing Suction Hopper Dredger became active in the Fehmarnbelt. Along with the dredgers, a number of other vessels, mainly tugs and barges were used to transport the sediment to land reclamation areas on the Danish side.

In total, about 70 vessels have been involved in all kinds of construction works in 2021. All these vessels have been tagged in the Quonops© model to assign their sound immissions to the Project. For representative project vessels, the source levels were measured by the construction companies via their subconsultant and have been transposed to similar vessels. Such measurements for different vessels and vessel activities are based on measurements in all four directions of each vessel and are used for the model as source level.

The approach taken for the underwater sound survey made it possible to establish routine procedures for comparing modelled and measured underwater noise and possible comparison metrics as well as to coordinate all participants to agree on a data format for transmission and on the means of data transmission.

The Quonops© model, regularly checked and calibrated with in-situ measured data with approximatively less than 1 dB deviation, has proven to be a good method for modelling the underwater noise of the construction work for the immersed tunnel and to assess conformity with the indicators in near real time. This result is obtained despite the challenging maritime context of a large number of sources of sound interfering with the sounds of the Project.

The Quonops© operational platform has demonstrated its reliability, providing modelling results and an assessment of the underwater noise indicators required by the authorities every 15 minutes around the clock since the start of the monitoring.

Figure 6. Dredging works close to Fehmarn in October 2021. Image: Femern A/S.

The example noise maps presented in Figure 7 illustrate that project noise at that time was well below and completely masked by the ambient noise from other shipping activities in the Fehmarnbelt. Modelling project noise is thus the only possibility to demonstrate compliance with the specific conditions for the Project. While most project vessels were operated stationary and mechanical grab and backhoe dredgers only produced moderate noise immissions, the ambient noise originating from larger vessels and ferries crossing the Fehmarnbelt at higher speeds of mostly 10 to 16 knots frequently produced higher noise immissions than construction vessels. Until December 2021 the modelled construction noise complied with the noise threshold indicators. The most relevant times for the Project with respect to underwater noise, however, are still ahead at this time, and for early 2022, two large trailing suction hopper dredgers are scheduled to operate in the Fehmarnbelt successively. Project noise was predicted to reach highest levels by then but are predicted to stay within the limits defined by the Plan Approval decision. The experience from the first half year of modelling and monitoring of construction noise provide sufficient confidence that the approach outlined in this paper will allow a solid assessment of the expected loudest phase of the Project.

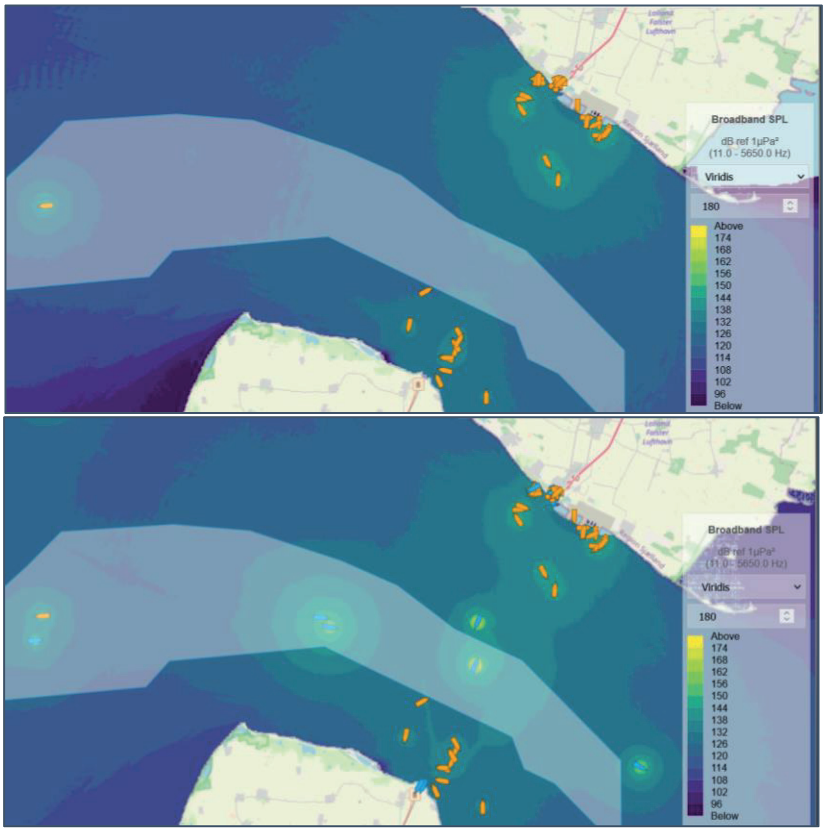

Figure 7. Noise maps showing a snapshot of construction sounds (top) and total underwater sounds (bottom) modelled by Quonops© on the 22 January 2022. Project vessels are represented in orange, while non-project vessels are marked in blue. The Fehmarn Natura 2000 area is shown as a semi-transparent polygon.

4 CONCLUSIONS AND LESSONS LEARNED

The results of the first months of real-time modelling and measuring underwater noise of the dredging work revealed a good fit of modelled underwater noise with the measurements. Therefore, Project-related sound across the Fehmarn belt can be predicted confidently and with sufficient accuracy to assess compliance with the regulation thresholds for underwater noise despite the interference with the sounds introduced by the heavy commercial traffic.

The first six months of underwater noise modelling and measurements further showed that a close coordination and good communication between the construction companies and the environmental construction monitoring is key for success. 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.

During the first phase of the Project, underwater noise modelling was accompanied by extensive noise measurements which allowed routine calibration of the model and gave assurance to the authorities that no unforeseen events of high noise immissions remained undetected. However, as no such events of high noise immissions occurred, the effort to measure underwater noise may be reduced after the necessary intensive measurement period that is mandatory to gain confidence and knowledge. The stability of the model has been achieved thanks to the numerous measurement stations, but it is now envisioned that fewer measurements might be sufficient to carry on the assessment of the indicators without compromising the quality of the survey.

The first six month of continuous real-time noise monitoring at a large dredging operation proved to be successful and the approach can be recommended to other projects where the occurrence of protected species may require managing underwater noise immissions.

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