UDK/*UDC*: 504.6:629.5.015.6(26)
Pregledni znanstveni članek – *Review paper*
DOI: 10.15292/acta.hydro.2025.10

Prejeto/*Received:* 26.09.2025
Sprejeto/*Accepted:* 15.01.2026
Objavljeno na spletu/*Published online:* 26.08.2026

MEASURES TO REDUCE ANTROPOGENIC NOISE IN THE SEA

UKREPI ZA ZMANJŠEVANJE ANTROPOGENEGA HRUPA V MORJU

Andreja Popit[1]

[1] Inštitut za vode Republike Slovenije, Einspielerjeva 6, Ljubljana, andreja.popit@izvrs.si

Abstract

This study aimed to review the measures for anthropogenic underwater noise reduction in European countries. The methodology for the literature review was based on specific keywords described in the paper. Selection criteria for including (and excluding) studies were based on underwater noise generated by anthropogenic activities (i.e. impact pile driving, seismic surveys, marine traffic) in seawater.

The main operational measure to reduce continuous noise from vessel traffic is speed reduction. The most commonly implemented measures to reduce impulsive noise due to pile driving and the use of explosives are bubble curtains and hydro sound dampers, while essential measures to reduce impulsive noise due to seismic surveys are low-frequency acoustic sources.

National approaches (e.g. Germany, Netherlands, Denmark, France, Slovenia) and regional guidelines (HELCOM, OSPAR, ACCOBAMS, IMO, CMS) show a high level of convergence in recommended technologies and environmental practices to reduce underwater noise. Harmonization of mitigation measures across European countries is critical for achieving a Good Environmental Status (GES) under the EU Marine Strategy Framework Directive (2008/56/EC).

Underwater noise mitigation measures aligned with the international guidelines, national reports, and scientific literature reviewed in this paper form the basis for developing national programs of measures and regulatory frameworks to manage underwater noise in the marine environment.

Keywords: anthropogenic underwater noise, noise mitigation, speed reduction of ships, big air bubble curtains, hydro sound dampers, underwater noise regulations and policy.

Izvleček

Namen te študije je bil pregled ukrepov za zmanjšanje antropogenega podvodnega hrupa v evropskih državah. Metodologija za pregled literature je temeljila na specifičnih ključnih besedah, opisanih v članku. Izbirna merila za vključitev (in izključitev) študij so temeljila na podvodnem hrupu, ki ga povzročajo antropogene dejavnosti (npr. udarno zabijanje pilotov, seizmične raziskave, pomorski promet) v morju.

[1] Stik / *Correspondence*: andreja.popit@izvrs.si

Najpomembnejši operativni ukrep za zmanjšanje kontinuirnega hrupa zaradi ladijskega prometa je zmanjšanje hitrosti ladij. Najpogosteje uporabljena ukrepa za zmanjšanje impulznega hrupa zaradi udarnega zabijanja pilotov in uporabe eksploziva so zavese iz zračnih mehurčkov in vodni dušilci zvoka, medtem ko je pri impulznem hrupu zaradi seizmičnih raziskav ključni ukrep uporaba nizkofrekvenčnih akustičnih virov.
Nacionalni pristopi (npr. v Nemčiji, Sloveniji, Franciji, na Nizozemskem, Danskem) in regionalne usmeritve (HELCOM, OSPAR, ACCOBAMS, IMO, CMS) kažejo visoko stopnjo skladnosti glede priporočenih tehnologij in okoljskih praks za zmanjšanje podvodnega hrupa. Za doseganje dobrega okoljskega stanja po Okvirni direktivi o morski strategiji (2008/56/ES) je ključna uskladitev ukrepov za zmanjšanje hrupa med evropskimi državami.
Ukrepi za zmanjšanje podvodnega hrupa, ki so usklajeni z mednarodnimi smernicami, nacionalnimi poročili in znanstveno literaturo, in so bili pregledani v tem članku, predstavljajo osnovo za oblikovanje nacionalnih programov ukrepov in regulativnih okvirov za upravljanje podvodnega hrupa v morskem okolju.

Ključne besede: antropogeni podvodni hrup, zmanjšanje hrupa, zmanjšanje hitrosti ladij, velike zavese iz zračnih mehurčkov, vodni dušilci zvoka, predpisi in politike glede podvodnega hrupa.

1. Introduction

Sound in the underwater environment is generated by animal calls, by geophysical phenomena such as rain, waves, water currents, and tectonic processes, and by human activities. Continuous anthropogenic sound is produced by maritime traffic, dredging activities, the operational sound of wind farms, and oil platforms. Impulsive anthropogenic sound is generated by pile driving, seismic exploration, the use of sonar, and explosions. The duration of the impulsive sound is less than 10 seconds, but it is intense.

Studies around the world have shown that both continuous and impulsive underwater noise could have potentially harmful effects on marine animals. Continuous low-frequency noise has a lower impact on marine mammals and fish than impulsive noise, such as masking communication, disrupting foraging, and altering migration patterns. Impulsive noise can cause physiological stress and hearing damage (Southall et al., 2017; Scott, 2004). An example of the impact of impulsive noise is found in 17 stranded whales near the coast of the Canary Islands when NATO tested an active sonar system in September 2002 (Scott, 2004). In order to decrease the negative impacts of anthropogenic noise on marine life, it is necessary to implement specific protective measures.

Underwater noise was first addressed in European legislation through the adoption of the EU Marine Strategy Framework Directive (MSFD) in 2008, in which it was included as the eleventh descriptor for establishing the Good Environmental Status (GES) of European marine waters (2008/56/EC). MSFD Article 13 is about the programs of measures to be taken at national level in order to achieve good environmental status in marine waters.

Within the International Maritime Organization (IMO), Guidelines for the reduction of underwater noise from commercial shipping were developed in 2014, which were revised in 2023 (IMO, 2014; 2023) and include a variety of mitigation measures.

The OSPAR Commission, as part of the Oslo and Paris Convention (OSPAR), published an inventory of measures to mitigate the emission and environmental impact of underwater noise in 2014, upgrading it in 2020 (Merck et al., 2014; 2020). The report by the OSPAR Commission considers the need to mitigate the impulsive noise generated by various kinds of human activities such as pile driving, seismic exploration, sonar use, and explosions (Merck et al., 2014).

The outcome of the Baltic Marine Environment Protection Commission meeting, known as the Helsinki Commission (HELCOM) meeting in 2016, was a set of measures to mitigate underwater noise produced by shipping, pile driving, seismic surveys, naval sonars, dredging, and explosives (HELCOM, 2016).

In the framework of the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea, and contiguous Atlantic area (ACCOBAMS), guidance on underwater noise mitigation measures was prepared in 2016, which was updated in 2019 and 2022 (ACCOBAMS, 2016; 2019; 2022).

The aim of this study was to review the mitigation measures for anthropogenic underwater noise reduction in guidelines and recommendations by IMO, OSPAR, HELCOM, and ACCOBAMS, together with national reports and scientific literature, which will form the basis for developing national programs of measures and regulatory frameworks for underwater noise management.

2. Materials and methods

The methodology for the literature review was based on specific keywords. First, "methodological guidance on underwater noise mitigation measures" was reviewed. The search methodology for the scientific papers was continued using the keyword "underwater noise mitigation measures". Then, "ship underwater radiated noise mitigation measures" was searched in the database. Furthermore, the keywords "underwater noise reduction" and "underwater noise abatement" were used to collect papers addressing this topic. This search was refined with a more specific topic, such as "speed reduction". The search was concluded with the keywords "underwater noise regulations" and "underwater noise policy" in order to review legal developments in relation to the mitigation measures.

Databases searched in this study include Google Scholar, Google Search, and ScienceDirect.

Selection criteria for including (and excluding) studies were based on underwater noise generated by anthropogenic activities in the seawater.

3. Results and discussion

3.1 General mitigation measures

General mitigation measures for underwater noise reduction are: measures that reduce source level (e.g. using the lowest possible source level or modification of noise source by reducing ship speed), measures that attenuate noise produced (e.g. using best available technologies), measures that reduce the likelihood of marine animals encountering a noise event (e.g. spatiotemporal exclusion or limitation of noise generating activities to protect marine species from disturbance at the most sensitive time of their life cycle) and usage of alternative techniques with lower sound emissions (Merck et al., 2014; HELCOM, 2016; Lamoni and Tougaard, 2023).

3.2 Mitigation measures for anthropogenic continuous underwater noise reduction from shipping

Underwater noise from ships is caused mainly by propeller cavitation, by machinery noise, and hull vibrations (IMO, 2010; 2014; McKenna et al., 2012; Arveson and Vendittis, 2000; Trevorrow and Vasiliev, 2008; Ross, 1976; IMO, 2010; Abrahamsen, 2012; Audoly and Rousset, 2014; Leaper et al., 2014; Spence and Fischer, 2016; Lee, 2017; Southall et al., 2017; Smith and Rigby, 2022; Cruz et al., 2022).

Typical underwater noise levels of large merchant ships range from 180 dB re 1μPa to 195 dB re 1μPa and often predominate in the low-frequency ambient noise of many oceans and seas (McKenna et al., 2012; 2013; Götz et al., 2009; Veirs et al., 2016). In this regard, reducing underwater noise from shipping is the most effective measure to lower ambient underwater noise levels in the oceans (Leaper et al., 2014; Leaper and Renilson, 2012; Findlay et al., 2023). The first mitigation solution would be to reduce the underwater noise emission of the noisiest 10% of ships (Leaper and Renilson, 2012; Audoly et al., 2015). Leaper (2019) concluded that a 10% speed reduction could reduce the total sound energy from shipping by around 40%. Namely, the reduction of ambient underwater noise is important for achieving a good environmental status (GES) of marine waters (Dekeling et al., 2014).

3.2.1 Mitigation measures used in ship (propeller and hull) design

Cavitation as the dominant radiated noise source from ships could be reduced through proper design, as it is the optimization of propeller load to provide as uniform water flow into the propellers as possible, as well as choosing appropriate propeller characteristics such as diameter, number of blades, blade area and shape, fixed or controllable blade angles (pitch), and skew (IMO, 2014; Renilson et al., 2013; De Jong and Hulskotte, 2021). The best available technologies for reducing propeller cavitation are presented in Table 1 (ACCOBAMS, 2019).

Hull form affects the inflow of water to the propeller. Thus, to effectively reduce underwater noise, hull and propeller design should be adjusted to each other (IMO, 2014). Uneven or non-homogeneous wake fields would increase cavitation. Therefore, the ship hull form should be designed so that the wake field is as homogeneous as possible (IMO, 2014; De Jong and Hulskotte, 2021).

3.2.2 Mitigation measures used in the design, selection, and installation of onboard machinery

Reduction of underwater noise and noise on board the ship can be achieved by the appropriate selection of ship machinery, devices, and equipment (IMO, 2014). Four-stroke diesel engines cause significantly less vibration and noise than two-stroke diesel engines. Thus, four-stroke engines are more suitable from the point of view of reducing underwater noise. Diesel-electric propulsion is an effective option to reduce underwater noise. The use of high-quality electric motors could help reduce vibrations induced in the hull.

An effective noise reduction measure would be the installation of diesel engines on resilient elastic mounts. Vibration isolation of ship devices and equipment would also be beneficial as a mitigating measure (IMO, 2014; Spence and Fischer, 2016).

Structural noise from ship engines could be reduced by lining the hull and deck with viscoelastic materials that dampen vibrations (IMO, 2014; Turner, 1969; Buiten, 1972; Nilson, 1978). In this regard, ACCOBAMS proposed some structural solutions, e.g. structural damping, increased hull thickness, and the use of lightweight materials like fiber-reinforced plastic (ACCOBAMS, 2019).

Table 1: *Best available technologies for reduction of propeller cavitation (ACCOBAMS, 2019).*

Preglednica 1: *Najboljše razpoložljive tehnologije za zmanjšanje kavitacije propelerja (ACCOBAMS, 2019).*

Best available technologies	Description of technology
Schneekluth duct	A device installed on the ship's hull to improve the flow on the upper part of the propeller and decrease cavitation.
Becker Mewis duct	A duct positioned in front of the propeller, along with an integrated fin system.
Propeller boss cap fins	Improves the propeller performance characteristics by minimizing the hub vortex and resultant rudder cavitation.
EnergoProFin (Wartsila)	An energy-saving propeller cap with fins that rotate together with the propeller.
ECO-Cap (Nakashima)	Propeller cap for propeller hub reduction.

3.2.3 Mitigation measures based on the use of additional technologies on existing ships

Additional technologies, such as state-of-the-art propellers, wake conditioning devices, and air injection systems, could be used to further reduce underwater noise (IMO, 2014; ACCOBAMS, 2019).

3.2.4 Mitigation measures used in ship operation and maintenance

Maintenance mitigation measures include cleaning the propellers and ship hull surface, whereas operational measures include selecting an optimal vessel speed and rerouting the ship to avoid ecologically sensitive areas (IMO, 2014; Audoly et al., 2015; 2017).

Marine fouling could be removed from the propeller through proper polishing, which reduces surface roughness and thereby helps to minimize propeller cavitation (IMO, 2014).

The ship's energy efficiency could be improved by maintaining a smooth underwater hull surface and paintwork, which reduces the ship's resistance and propeller load, and thereby lowers underwater noise (IMO, 2014).

A pilot study conducted in British Columbia (Canada) and the Santa Barbara Channel (California) demonstrated that slowing commercial vessels to 11 knots or less is an effective method for reducing underwater radiated noise (MacGillivray et al., 2019; ZoBell et al., 2021). A study on modeling underwater noise levels in the Slovenian Sea showed that modeled values were mainly affected by the speed of the ships. Therefore, adjusting ship speed is an effective measure for controlling underwater noise from shipping in the world’s seas and oceans (Popit and Čurović, 2022).

The particular speed of the ship that would be maintained would be dependent on safety, operation, and energy efficiency. Critical ship speed should be avoided because of the effects of cavitation and the consequent increased emission of continuous underwater noise (IMO, 2014). Optimum combinations of shaft speed and propeller pitch should be taken into account in order to reduce the effects of cavitation and, with this, reduce the underwater noise (IMO, 2014; Findlay et al., 2023).

Reducing the speed of ships or rerouting ships outside sensitive marine areas with well-known habitats or migratory pathways, especially during migration periods, would help reduce the harmful effects of underwater noise on marine organisms (IMO, 2014; Southall et al., 2017; Chion et al., 2017).

3.3 Mitigation measures for the reduction of anthropogenic impulsive underwater noise

3.3.1 Real-time mitigation practices

Acoustic Mitigation Devices (AMDs) should be activated prior to underwater noise-generating activities, allowing marine mammals sufficient time to leave the area. AMDs should be operated for a minimum of 10 minutes (Merck et al., 2020; ACCOBAMS, 2022).

Underwater noise emissions should begin with a *Soft Start Protocol* (SSP), which requires that noise emissions begin at low power and then increase in equal steps until full power is reached. The duration of the soft start protocol should be at least 15 minutes. After 10 minutes of sound source inactivity, the SSP should be implemented again before restarting activities (Merck et al., 2020; ACCOBAMS, 2022).

The Marine Mammal Observation Protocol (MMOP), also known as the visual monitoring protocol, requires that independent marine mammal observers monitor the Exclusion Zone (EZ) for 30 minutes before the commencement of the SSP (120 minutes for highly sensitive species). The SSP should be delayed if cetaceans enter the EZ. Continuous marine mammal observation should be implemented for the entire duration of the noise emission. Noise emissions should be stopped if cetaceans enter the EZ. In that case, a new 30-minute marine mammal observation period should be implemented without animals in the EZ before resuming with noise emissions (120 minutes for highly sensitive species). In the event that endangered species appear anywhere in the monitoring area, noise emissions should be stopped immediately (Merck et al., 2020; ACCOBAMS, 2022).

The *Passive Acoustic Monitoring Protocol* (PAMP) should be implemented to alert marine mammal observers about the presence of cetaceans. PAMP should be carried out for the entire duration of the noise emissions. In the event that impulsive sound sources are used at night or in poor weather conditions, PAMP should serve as the primary monitoring tool. In the case that acoustic detection identifies cetaceans, all noise emissions should be stopped immediately (Merck et al., 2020; ACCOBAMS, 2022).

3.3.2 Mitigation measures to be used for pile driving

Pile driving is used in many coastal and offshore constructions, such as harbor extensions, wind farms, and offshore oil platforms (ACCOBAMS, 2019; 2022). The parameters of the sound source used in pile driving are presented in Table 2.

Pile driving is potentially harmful to marine animals, especially marine mammals. Underwater noise generated by pile driving depends mainly on the hammer impact energy and pile diameter. Measurements presented by Bellmann (2014) have shown values of up to 180 dB for the sound exposure level (*SEL*) and up to 205 dB for the peak level (L_{Peak}).

The regulatory authority in Germany has set limit values for sound exposure level (*SEL* = 160 dB re 1μ Pa^2) and for peak level (L_{Peak} = 190 dB re 1μ Pa), which must be taken into consideration within a distance of 750 m from the construction site (Bellman, 2014).

Mitigation measures in the planning phase, during impulsive noise emissions, and post-activity practices are described in Table 3.

Table 2: *Parameters of the impulsive sound sources used in pile driving, seismic surveys, explosive use, and sonar use (LFAS and MFAS are low- and mid-frequency active sonars) (ACCOBAMS, 2019; 2022).*

Preglednica 2: *Parametri impulznih virov zvoka, uporabljenih pri zabijanju pilotov, seizmičnih raziskavah, uporabi eksplozivov in uporabi sonarja (LFAS in MFAS sta nizko- in srednjefrekvenčna sonarja) (ACCOBAMS, 2019; 2022).*

Parameters of the sound source	Pile driving	Seismic surveys	Explosive use	Sonar use
Source level	228 dB re 1μPa m (Peak) or 243–257 dB re 1μPa m (P-to-P)	220–262 dB re 1μPa m (P-to-P)	(0.5–50 kg) 272–287 dB re 1μPa m (Peak)	235 dB re 1μPa m (Peak, LFAS) 223–235 dB re 1μPa m (Peak, MFAS)
Bandwidth	20 Hz – 20 kHz	5 Hz – 100 kHz	2 Hz – 1 kHz	100–500 Hz (LFAS) 2–8 kHz (MFAS)
Major amplitude	100–500 Hz	10–120 Hz	6–21 Hz	3.5 kHz (MFAS)
Duration	50 ms	10–100 ms	1–10 ms	6–100 s (LFAS) 0.5–2 s (MFAS)
Directionality	omnidirectional	downwards	omnidirectional	horizontally focused

3.3.3 Mitigation measures to be used in seismic surveys

Marine seismic exploration is carried out using an airgun. Seismic surveys could be performed in shallow and deep water as well as in coastal or offshore regions. The parameters of the sound source of an airgun are presented in Table 2. Airgun use should be avoided, as far as possible, in areas that are important for cetaceans (ACCOBAMS, 2022). Proper mitigation measures should be carried out in the planning phase and during airgun use, and proper post-activity practices should be carried out (Table 4).

Table 3: *Mitigation measures to be used for pile driving in the planning phase, real-time mitigation practices, and post-activity practices (ACCOBAMS, 2019; 2022; Bellmann, 2014).*

Preglednica 3: *Omilitveni ukrepi pri udarnem zabijanju pilotov v fazi načrtovanja, v realnem času in po končani aktivnosti (ACCOBAMS, 2019; 2022; Bellmann, 2014).*

Mitigation measures in the planning phase	Real-time mitigation practices	Post-activity practices
- Overview of the presence of cetaceans in the proposed survey periods (or conduct research if the information is inadequate). - Select periods with low biological sensitivity. - Use sound propagation modelling results, verified in the field, in order to define the extent of the exclusion area. - Plan the lowest practicable source power. - Consider alternative technologies (drilled foundation, vibro-drilling, bucket foundation).	- Use noise mitigation technologies when no alternatives are possible, such as: single or double big bubble curtain, small air bubble curtain, hydro sound damper, cofferdam, IHC noise mitigation system, BEKA shells, and tunable resonator system. - Use acoustic mitigation devices before beginning work. - Use the soft start protocol. - Use the visual monitoring protocol. - Use the passive acoustic monitoring protocol.	- Detailed reporting of real-time mitigation measures.

Table 4: *Mitigation measures to be used in seismic surveys in the planning phase, real-time mitigation practices, and post-activity practices (Merck et al., 2020; HELCOM, 2016; ACCOBAMS, 2019; 2022).*

Preglednica 4: *Omilitveni ukrepi pri seizmičnih raziskavah v fazi načrtovanja, v realnem času in po končani aktivnosti (Merck et al., 2020; HELCOM, 2016; ACCOBAMS, 2019; 2022).*

Mitigation measures in the planning phase	Real-time mitigation practices	Post-activity practices
- Consider the use of alternative technologies (i.e. marine vibroseis, low-frequency acoustic sources, electromagnetic surveys, gravity and gravity gradiometry, shear wave generators). - Overview of the presence of cetaceans in the proposed survey periods (or conduct research if the information is inadequate). - Exclusion or restriction of activities generating impulsive underwater noise at certain times of the year and in certain areas. - Define no-seismic survey zones (biological reserves, specially protected areas, etc.). - Select periods with low biological sensitivity. - Use sound propagation modelling to define the extent of the exclusion area. - Use the lowest possible source level.	- Use acoustic mitigation devices before the beginning of the sound emission. - Use the soft start protocol. - Use the visual monitoring protocol. - Use the passive acoustic monitoring protocol.	- Detailed reporting of real-time mitigation measures.

3.3.4 Mitigation measures for explosive use

Underwater explosions could be planned for maritime construction (i.e. fragmenting rock before dredging) or used for naval military exercises. Detonation could also occur during explosive deactivation (ACCOBAMS, 2019; 2022). The parameters of the sound source for explosions are presented in Table 2. Explosives are the loudest source of underwater noise; thus, mitigation measures described in Table 5 should be carried out to minimize harmful effects on marine organisms.

3.3.5 Mitigation measures for sonar use

Low-, mid-, and high-frequency active sonars are used for military exercises as well as for academic and industrial surveys, such as fish stock estimations and bathymetric surveys (ACCOBAMS, 2019; 2022). The parameters of the sound source of the sonar are presented in Table 2. Low- and mid-frequency naval sonars are the most harmful to marine animals. Namely, mass stranding events of cetaceans were linked in space and time to military exercises (Scott, 2004). High-powered active sonar should be avoided, as far as possible, in areas that are important for cetaceans (ACCOBAMS, 2022). Mitigation measures for sonar use are presented in Table 6.

3.4 Discussion of mitigation measures for the reduction of continuous and impulsive underwater noise in European countries

Measures for anthropogenic underwater noise reduction in the Baltic were described in the Report of the HELCOM SOM project (Lamoni and Tougaard, 2023). Measures to reduce impulsive noise from pile driving in the Baltic (i.e. bubble curtains, hydro sound dampers, isolation casings, cofferdams) are similar to measures described in the ACCOBAMS guidance for the Black Sea, Mediterranean Sea, and contiguous Atlantic area (ACCOBAMS, 2022), as well as in the OSPAR inventory of measures (Merck et al., 2014; 2020). Mitigation of military sonars in the Baltic includes avoidance of sensitive areas, implementation of operational procedures, and exclusion zones (Lamoni and Tougaard, 2023), which are similar to those described in the ACCOBAMS guidance (ACCOBAMS, 2022).

Operational measures to mitigate continuous noise from ships due to cavitation in the Baltic are regular propeller and hull maintenance, and vessel speed and routing control (Lamoni and Tougaard, 2023), which are similar to measures in the IMO guidelines (IMO, 2014). Technical solutions to reduce ship noise in the Baltic include coating the propeller surface, high-skew propellers, Kappel propellers, new blade section propellers, controllable pitch propellers, wake inflow devices, Mewis ducts, and Schneekluth ducts (Lamoni and Tougaard, 2023), which are similar to those proposed in the ACCOBAMS guidance on underwater noise mitigation measures (ACCOBAMS, 2022).

The Danish Energy Agency has prepared guidelines on underwater noise reduction measures during the installation of impact-driven piles for the construction of offshore wind farms (Danish Energy Agency, 2022). Primary measures include direct mitigation of the noise-generating mechanism (e.g. use of alternative hammer technologies and impact pulse prolongation devices). Secondary measures include the introduction of noise barriers in the propagation path (e.g. bubble curtains, hydro sound dampers, and double-walled steel cylinders as isolation casings). These reduction measures are similar to mitigation measures proposed in the ACCOBAMS guidance (ACCOBAMS, 2022) and in the OSPAR inventory of measures (Merck et al., 2014; 2020).

Table 5: *Mitigation measures for explosive use in the planning phase, real-time mitigation practices, and post-activity practices (ACCOBAMS, 2019; 2022).*

Preglednica 5: *Omilitveni ukrepi pri uporabi razstreliva v fazi načrtovanja, v realnem času in po končani aktivnosti (ACCOBAMS, 2019; 2022).*

Mitigation measures in the planning phase	Real-time mitigation practices	Post-activity practices
- Overview of the presence of cetaceans in the proposed survey periods (or conduct research if the information is inadequate). - Exclusion or restriction of activities generating impulsive underwater noise at certain times of the year and in certain areas. - Select periods with low biological sensitivity. - Use sound propagation modelling results to define the extent of the exclusion area. - Plan the lowest practicable source power.	- Use noise mitigation technologies: • big air bubble curtain • hydro sound damper. - Use acoustic mitigation devices before the beginning of the sound emissions. - Use the soft start protocol. - Use the visual monitoring protocol. - Use the passive acoustic monitoring protocol.	- Detailed reporting of real-time mitigation measures.

Table 6: *Mitigation measures for sonar use in the planning phase, real-time mitigation practices, and post-activity practices (ACCOBAMS, 2019; 2022).*

Preglednica 6: *Omilitveni ukrepi pri uporabi sonarja v fazi načrtovanja, v realnem času in po končani aktivnosti (ACCOBAMS, 2019; 2022).*

Mitigation measures in the planning phase	Real-time mitigation practices	Post-activity practices
- Overview of the presence of cetaceans in the proposed survey periods (or conduct research if the information is inadequate). - Exclusion or restriction of activities generating impulsive underwater noise at certain times of the year and in certain areas. - Define no-sonar use zones (biological reserves, specially protected areas, etc.). - Define protected zones. - Select periods with low biological sensitivity. - Use sound propagation modelling to define the extent of the exclusion area.	- Use the soft start protocol. - Use the visual monitoring protocol. - Use the acoustic monitoring protocol.	- Detailed reporting of real-time mitigation measures.

The French Ministry of the Ecological Transition and Solidarity has developed recommendations to limit the impacts of anthropogenic underwater noise on marine wildlife (Persohn et al., 2020). These guidelines include mitigation measures for seismic surveys (use of the smallest possible source of impulsive noise, use of alternative technology such as "marine vibroseis"), impact pile driving (increasing the duration of hammer strikes, use of air bubble curtains, hydro sound dampers, isolation casings, and cofferdams, and use of alternative technologies such as gravity foundations, drilled piles, and vibratory pile driving), and mitigation measures for maritime traffic (proper design of hulls and propellers to reduce cavitation, maintenance of ship propellers and hulls and reduce ship speed). In addition, visual monitoring of marine mammals and acoustic monitoring of underwater noise, use of soft start protocol, and use of acoustic deterrents are recommended. French measures to mitigate underwater noise due to seismic surveys and impact pile driving are similar to those proposed in the OSPAR inventory of measures (Merck et al., 2014; 2020), in the ACCOBAMS guidance (ACCOBAMS, 2016; 2022), and in the HELCOM document (HELCOM, 2016). French measures to mitigate underwater noise due to maritime traffic are similar to those described in the IMO guidelines (IMO, 2014), the ACCOBAMS guidelines (ACCOBAMS, 2016; 2022), and the HELCOM document (HELCOM, 2016).

The best available technologies (BAT) and best environmental practices (BEP) for mitigating shipping noise, seismic airgun surveys, and pile driving were collected in the publication of the Convention on the Conservation of Migratory Species of Wild Animals (CMS), to which EU countries are also parties (Weilgart, 2023). Reduction of underwater noise from ships is possible by minimizing cavitation through optimization of the propeller and hull design. Hull vibration, engine, and machinery noise could be reduced using vibration isolation, noise insulation, and damping. Best environmental practices (BEP) for shipping noise reduction include slow steaming or reducing ship speed (which also reduces greenhouse gas emissions), better maintenance of ship propeller and hull, and rerouting shipping lanes around important habitats (Weilgart, 2023).

The best available technologies (BAT) for reducing noise from seismic airgun surveys, as published by CMS, include lowering source levels, reducing high-frequency content, and using marine vibroseis (Weilgart, 2023). The best environmental practices (BEP) for seismic airgun survey noise include baseline studies of biological abundance and distribution of sensitive species before the seismic survey, management of marine protected areas, use of the lowest practicable source power, modelling of the generated sound field in relation to oceanographic features (temperature profile, water depth, seafloor characteristics) to dynamically set the safety or exclusion zone, and continuous visual and passive acoustic monitoring. Further, airgun surveys should be prohibited at night, soft start procedures should be used, beginning of emissions should be delayed if sensitive species are observed within the exclusion zone, the sound source(s) should be shut down immediately whenever a sensitive species enters the exclusion zone, and a biological survey should be conducted after the seismic survey is completed (Weilgart, 2023).

The best available technologies (BAT) for reducing noise due to pile driving published by CMS include isolation casings, big bubble curtains, hydro sound dampers, vibro piling, blue piling, adapting hydraulic hammers to prolong impact force, using gravity foundations, drilling, and using floating wind turbines (Weilgart, 2023). The best environmental practices (BEP) for reducing noise during pile driving include long-term acoustical monitoring and research on the effects of offshore wind farms on marine life, modelling of the sound level emission of each wind farm, restrictions regarding the maximum duration of a piling operation for each pile, restrictions regarding the maximum energy used for pile driving, using acoustic deterrents, the soft start procedure, and monitoring of marine mammals (Weilgart, 2023).

BAT and BEP to mitigate underwater noise due to seismic airgun surveys and pile driving collected in the CMS publication are similar to those proposed in the OSPAR inventory of measures (Merck et al., 2014; 2020), in the HELCOM document (HELCOM, 2016), and in the ACCOBAMS guidance (ACCOBAMS, 2016; 2022). BAT and BEP to mitigate shipping noise collected in the CMS publication are similar to those described in the IMO guidelines (IMO, 2014), in the HELCOM document (HELCOM, 2016), and the ACCOBAMS guidance (ACCOBAMS, 2016; 2022).

The Dutch government incorporated mitigation measures for pile driving for wind farm construction in the Wind Energy at Sea Act (Strietman et al., 2018). Single stroke sound exposure levels (SEL_{SS}) using a hydro-hammer with energies up to 10 MJ are in the order of magnitude of 165–175 dB at a range of 750 m in 25–30 m of water depth if no noise mitigation measures are used (TNO, 2016). The maximum single-stroke sound exposure level (SEL_{SS}) at a distance of 750 m from the construction site permitted in the Netherlands varies between 159 dB and 172 dB, depending on the number of piles (Strietman et al., 2018). In Germany, the regulatory norm for the maximum (SEL_{SS}) is set at 160 dB within a distance of 750 m from the construction site, which is stricter than the norm applied in the Netherlands (Strietman et al., 2018).

Several underwater noise mitigation techniques are used in Dutch waters for pile installation i.e. isolation casings developed by Dutch company IHC IQIP, BLUE pilling developed by Dutch company Fistuca BV, which uses a column of water instead of a conventional hammer, vibratory pile driving technique, in which a vibratory hammer is used instead of an impact hammer, and technology using bubble curtains (Strietman et al., 2018).

In the Netherlands**,** several mitigation measures are used to mitigate continuous underwater noise generated by ships, such as cavitation-reducing technologies, engine noise insulation, slower cruising speed, and economic instruments, i.e. lower port fees for quieter ships (Strietman et al., 2018). These mitigation measures are similar to those proposed in the IMO guidelines (IMO, 2014), in the HELCOM document (HELCOM, 2016), and in the ACCOBAMS guidance (ACCOBAMS, 2016; 2022).

French scientists (Recuero Virto et al., 2022) proposed measures to reduce underwater noise from shipping in ports. Port actions could support underwater noise reduction through changes in propeller, hull, and engine design, as well as through operational mitigation measures, including speed reduction, changed ship routes, and travel in convoys. Ports could propose actions such as discounted port fees and reduced ship waiting times at ports, both according to underwater noise performance (Recuero Virto et al., 2022). Vakili et al. (2020) proposed the development of an underwater noise management plan within ports that would contribute to sustainable development.

A comparison of national regulations for pile driving used in wind farm construction in Belgium and the Netherlands has been described by Rumes et al. (2016). A wide range of noise mitigation systems has been developed, such as various types of bubble curtains, shell-in-shell systems, and hydro sound dampers. Belgian and Dutch governments formulated several measures to prevent and limit the impact of underwater noise on marine mammals during pile driving, such as seasonal noise limits or restrictions, the use of acoustic deterrent devices prior to pile driving, and the use of a soft start procedure. However, seasonal pile driving restrictions in Belgian and Dutch waters are different in timing. This example shows that regulatory practices should be aligned on a regional basis (Rumes et al., 2016).

The basic mitigation measure for continuous noise in the Slovenian Marine Environment Management Plan – SMEMP (Breznik et al., 2022) restricts noise emissions from recreational craft and personal watercraft in accordance with Directive 2013/53/EU. The Directive limits airborne noise emissions, which consequently also reduces underwater noise emissions. Additional mitigation measures for continuous noise included in the SMEMP are those adopted in the framework of the International Maritime Organisation – IMO, such as those described in Chapter 3.2 of this paper. Mitigation measures for impulsive noise included in the SMEMP are measures for reducing impulsive underwater noise from intermittent activities, such as pile driving, seismic surveys, explosive use, and sonar use, which are described in Chapter 3.3 of this paper.

The main source of continuous noise in the Slovenian Sea is marine traffic; thus, the most important noise mitigation measure for continuous noise in the Slovenian Sea would be speed reduction (Popit and Čurović, 2022). The main source of impulsive noise in the Slovenian Sea is pile driving. Thus, the most important mitigation measures would be the use of mitigation technologies, the use of acoustic mitigation devices before the beginning of the work, the use of a soft start protocol, the use of a visual monitoring protocol, and the use of passive acoustic monitoring (Table 3).

Incorporating underwater noise mitigation measures into Slovenian national regulation requires aligning existing environmental and maritime laws with the EU Marine Strategy Framework Directive and the Regional Seas Conventions' noise reduction guidelines, as well as best practices from EU countries. By adopting standardized monitoring methodologies and setting EU-aligned noise thresholds, enforcing noise restrictions in the existing Marine Protected Areas, and promoting noise-reducing technologies, Slovenia can effectively protect its marine environment. Engaging stakeholders and fostering regional cooperation with Italy and Croatia are essential for addressing transboundary noise impacts and meeting international obligations.

3.5 Synthesis of future underwater noise mitigation strategies in European countries

Reduction of continuous underwater noise from shipping should be addressed through optimization of propeller characteristics and hull forms to minimize cavitation. In addition, the selection of low-vibration machinery like four-stroke diesel engines on elastic mounts would reduce underwater noise. The use of technologies such as wake conditioning devices and air injection to propellers, combined with maintenance practices like hull cleaning and propeller polishing, would reduce the noise. Operational measures, including 10% speed reductions, could reduce the total sound energy by 40%, while rerouting would avoid sensitive habitats. Future EU policies under MSFD could incentivize adoption via port fees for quieter vessels.

Real-time mitigation practices, including the use of acoustic mitigation devices, the soft start protocol, the marine mammal observation protocol, and the passive acoustic monitoring protocol, are recommended for reducing underwater noise from impulsive noise sources. The use of noise mitigation technologies is recommended for pile driving (such as single or double big bubble curtain, small air bubble curtain, hydro sound damper, cofferdam, IHC noise mitigation system, BEKA shells, and tunable resonator system), as well as alternative technologies (such as drilled foundation, vibro-drilling, bucket foundation). The use of alternative technologies is recommended for seismic surveys (such as marine vibroseis, low-frequency acoustic sources, electromagnetic surveys, gravity and gravity gradiometry, shear wave generators). The use of noise mitigation technologies is recommended for explosive use (such as big air bubble curtains and hydro sound dampers) (ACCOBAMS, 2022; OSPAR, 2020; HELCOM 2016).

The harmonization of mitigation measures across European countries is critical for achieving Good Environmental Status (GES) under the EU Marine Strategy Framework Directive (2008/56/EC), incorporating best available technologies and best environmental practices as referenced in guidelines from IMO, OSPAR, HELCOM, and ACCOBAMS. At the national level, each EU country must develop programs of measures, under MSFD Article 13, for local marine waters. It is important to establish noise thresholds, mandatory environmental impact assessments for noise-generating activities, and the integration of mitigation measures into permitting processes for shipping, construction, and surveys. At the regional level, sub-regional cooperation through bodies like OSPAR (North-East Atlantic), HELCOM (Baltic Sea), and ACCOBAMS (Mediterranean and Black Seas) is required to align transboundary standards, share registries of noise sources, standardize monitoring methodologies, and enforce harmonized thresholds to mitigate cumulative impacts across shared ecosystems.

4. Conclusions

MSFD (2008/56/EC) required the achievement of Good Environmental Status (GES) of European marine waters by 2020, which has not been met yet. When an individual member state is not able to achieve GES, the application of mitigation measures proposed by IMO, ACCOBAMS, OSPAR, and HELCOM guidelines and mitigation practices used in European countries reviewed in this paper would be essential to move toward GES.

Underwater noise mitigation measures aligned with IMO, ACCOBAMS, OSPAR, and HELCOM guidelines, national reports, and scientific literature reviewed in this paper form the basis for developing national programs of measures and regulatory frameworks to manage underwater noise in the marine environment. Although some regulations at the national level already exist, these regulatory frameworks should be harmonized between EU countries at the sub-regional and regional level.

Declaration of interests

I declare that I have no conflict of interest.

Data availability statement

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Funding

This study was funded by the Ministry of the Environment, Climate and Energy, Slovenian Environment Agency and the Ministry of Natural Resources and Spatial Planning.

References

Abrahamsen, K. (2012). The ship as an underwater noise source. Proceedings of Meetings on Acoustics, Edinburgh, 1–10.

ACCOBAMS (2016). Methodological guide – Guidance on underwater noise mitigation measures. Sixth Meeting of the Parties to ACCOBAMS, Monaco, 22 p.

ACCOBAMS (2019). Methodological guide – Guidance on underwater noise mitigation measures. Seventh Meeting of the Parties to ACCOBAMS, Istanbul, 31 p.

ACCOBAMS (2022). Methodological guide – Guidance on underwater noise mitigation measures. Eighth Meeting of the Parties to ACCOBAMS, Malta, 31 p.

Arveson, P.T., Vendittis, D.J. (2000). Radiated noise characteristics of a modern cargo ship, *Journal of the Acoustical Society of America* **107**, 118–129. https://doi.org/10.1121/1.428344.

Audoly, C., Rousset, C. (2014). European project for achieving quieter oceans by shipping noise footprint reduction. 167th Meeting of the Acoustical Society of America, Providence, Rhode Island, 1–15.

Audoly, C., Rousset, C., Rizzuto, E., Salinas Mullor, R., Hallander, J., Baudin, E. (2015). Mitigation measures for controlling the ship underwater radiated noise, in the scope of AQUO project. Conference OCEANS 2015, Genova. https://doi.org/10.1109/OCEANS-Genova.2015.7271381.

Audoly, C., Gaggero, T., Baudin, E., Folegot, T., Rizzuto, E., Salinas Mullor, R., Andre, M., Rousset, C., Kellett, P. (2017). Mitigation of underwater radiated noise related to shipping and its impact on marine life: A practical approach developed in the scope of AQUO Project, *IEEE Journal of Oceanic Engineering* **42(2)**, 373–387. https://doi.org/10.1109/JOE.2017.2673938.

Bellmann, M.A. (2014). Overview of existing Noise Mitigation Systems for reducing Pile-Driving Noise. Inter.noise 2014, Melbourne, 1–11.

Breznik, B., Bricelj, M., Klančnik, K., Koren, Š., Caserman, H., Jarni, K., Kovač Viršek, M., Popit, A., Robič, U., Kaučič, R., Trdan, Š., Šantl, S., Orlando-Bonaca, M., Mavrič, B., Lipej, L., France, J., Bajt, O., Čermelj, B., Mozetič, P., Petelin, B., Malačič, V., Turk, V., Šiško, M. (2022) *Načrt upravljanja z morskim okoljem (Marine Environment Management Plan)*. Ministry of Natural Resources and Spatial Planning of the Republic of Slovenia, Ljubljana, 202 p.

Buiten, J. (1972). Noise reduction on a Rhine-cruise ship due to damping material, *Journal of Sound Vibration* **21(2)**, 159–167.

Chion, C., Lagrois, D., Dupras, J., Turgeon, S., McQuinn, I.H., Michaud, R., Ménard, N., Parrott, L. (2017): Underwater acoustic impacts of shipping management measures: Results from a social-ecological model of boat and whale movements in the St. Lawrence River Estuary (Canada), *Ecological Modelling* **354**, 72–87. https://doi.org/10.1016/j.ecolmodel.2017.03.014.

Cruz, E., Lloyd, T., Lafeber, F.H., Bosschers, J., Vaz, G., Djavidnia S. (2022). The SOUNDS project: towards effective mitigation of underwater noise from shipping in Europe. Proceedings of Meetings on Acoustics, Southampton, 1–14. https://doi.org/10.1121/2.0001638.

Danish Energy Agency (2022). Guideline for underwater noise – Installation of impact or vibratory driven piles. Danish Energy Agency, Kobenhavn, 44 p.

De Jong, C.A.F., Hulskotte, J.H.J. (2021). *Reduction of ship traffic emissions and underwater radiated noise – Part 2*. *Report R10560*. TNO, Hague, 58 p.

Dekeling, R.P.A., Tasker, M.L., Van der Graaf, A.J., Ainslie, M.A, Andersson, M.H., André, M., Borsani, J.F., Brensing, K., Castellote, M., Cronin, D., Dalen, J., Folegot, T., Leaper, R., Pajala, J., Redman, P., Robinson, S.P., Sigray, P., Sutton, G., Thomsen, F., Werner, S., Wittekind, D., Young, J.V. (2014): *Monitoring Guidance for Underwater Noise in European Seas Part I: Executive Summary*. *JRC Scientific and Policy Report*. Publications Office of the European Union, Luxembourg, 13 p. https://doi.org/10.2788/29293.

Directive of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive) (2008). Official Journal of the European Union, 2008/56/EC, L164, 19–40.

Findlay, C.R., Rojano-Donate, L., Tougaard, J., Johnson, M.P., Teglberg Madsen P. (2023). Small reductions in cargo vessel speed substantially reduce noise impacts to marine mammals, *Science Advances* **9(25)**, 1–11. https://doi.org/10.1126/sciadv.adf2987.

Götz, T., Hastie, G., Hatch, L.T., Raustein, O. (2009). *Overview of the impacts of anthropogenic underwater sound in the marine environment*. OSPAR Commission, London, 51 p.

HELCOM (2016). Underwater noise mitigation measures. Fifth Meeting of the Working Group on Reduction of Pressures from the Baltic Sea Catchment Area, Warsaw, 26 p.

IMO (2010). Noise from commercial shipping and its adverse impacts on marine life. 17th ASCOBANS Advisory Committee Meeting, Bonn, Report on the correspondence group 61/19, 8 p.

IMO (2014). Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life. International Maritime Organization (IMO) – Marine Environment Protection Committee (MEPC), London, Circ. 833, 6 p.

IMO (2023). Revised guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life. International Maritime Organization (IMO) – Marine Environment Protection Committee (MEPC), London, Circ. 906, 21 p.

Lamoni, L., Tougaard, J. (2023). *Measures for reduction of anthropogenic noise in the Baltic, Report to the HELCOM SOM project – Scientific Report No. 556*. Aarhus University, Aarhus, 61 p.

Leaper, R., Renilson, M. (2012). A review of practical methods for reducing underwater noise pollution from large commercial vessels, *International Journal of Maritime Engineering* **154(A2)**, 79–88. https://doi.org/10.3940/rina.ijme.2012.a2.227.

Leaper, R., Renilson, M., Ryan, C. (2014). Reducing underwater noise from large commercial ships: current status and future directions, *Journal of Ocean Technology* **9(1)**. 51–69.

Leaper, R. (2019). The role of slower vessel speeds in reducing greenhouse gas emissions, underwater noise and collision risk to whales, *Frontiers in Marine Science* **6(505)**, 1–8. https://doi.org/10.3389/fmars.2019.00505.

Lee, S.J. (2017). Towards Minimizing Underwater Noise from Ships, *Oceanography and Fisheries Open access Journal* **4(5)**, 1–2. https://doi.org/10.19080/OFOAJ.2017.04.555649.

MacGillivray, A.O., Li, Z., Hannay, D.E., Trounce, K.B., Robinson, O.M. (2019). Slowing deep-sea commercial vessels reduces underwater radiated noise, *Journal of the Acoustical Society of America* **146**, 340–351. https://doi.org/10.1121/1.5116140.

McKenna, M.F., Ross, D., Wiggins, S.M., Hildebrand, J.A. (2012). Underwater radiated noise from modern commercial ships, *The Journal of the Acoustical Society of America* **131(1)**, 92–103. https://doi.org/10.1121/1.3664100.

McKenna, M.F, Wiggins, S.M., Hildebrand, J.A. (2013). Relationship between container ship underwater noise levels and ship design, operational and oceanographic conditions, *Scientific Reports* **3(1760)**, 1–10. https://doi.org/10.1038/srep01760.

Merck, T., Werner, S., Koschinski, S., Lüdemann, K. (2014). *OSPAR inventory of measures to mitigate the emission and environmental impact of underwater noise*. OSPAR Commission, London, 41 p.

Merck, T., Werner, S., Koschinski, S., Lüdemann, K. (2020). *OSPAR inventory of measures to mitigate the emission and environmental impact of underwater noise*. OSPAR Commission, London, 74 p.

Nilson, A.C. (1978). Reduction of structure-borne sound in simple ship structures – results of model tests, *Journal of Sound Vibration* **61(1)**, 45–60.

Persohn, C., Helloco, L., Baudinière, E., Martinez, L. (2020). *Recommendations to limit the impacts of manmade underwater acoustic emissions on marine wildlife*. Ministere de la Transition Ecologique et Solidaire, Paris, 208 p.

Popit, A., Čurivić, L. (2022). Modelling underwater noise levels in the Slovenian Sea, *Polish Journal of Environmental Studies* **31(4)**, 3755–3765. https://doi.org/10.15244/pjoes/147132.

Recuero, Virto L., Dumez, H., Romero, C., Bailly, D. (2022). How can ports act to reduce underwater noise from shipping? Identifying effective management frameworks, *Marine Pollution Bulletin* **174**, 1–22. https://doi.org/10.1016/j.marpolbul.2021.113136.

Renilson, M., Leaper, R., Boisseau, O. (2013). Hydro-acoustic noise from merchant ships – impacts and practical mitigation techniques. Third International Symposium on Marine Propulsors, Launceston, Tasmania, 201–208.

Ross, D. (1976). *Mechanics of underwater noise*. Pergamon Press, New York, 375 p.

Rumes, B., Erkman, A., Haelters, J. (2016). "Evaluating underwater noise regulations for piling noise in Belgium and the Netherlands" in A.N. Popper, A. Hawkins, Eds., *Effects of anthropogenic noise on marine life*, Springer, 37–48.

Scott, K.N. (2004). International Regulation of Undersea Noise, *International & Comparative Law Quarterly* **53(2)**, 287–323. https://doi.org/10.1093/iclq/53.2.287.

Smith, T.A., Rigby, J. (2022). Underwater radiated noise from marine vessels: a review of noise reduction methods and technology, *Ocean Engineering* **266(112863),** 1–15. https://doi.org/10.1016/j.oceaneng.2022.112863.

Southall, B.L., Scholik-Schlomer, A.R., Hatch, L., Bergmann, T., Jasny, M., Metcalf, K., Weilgart, L., Wright, A.J. (2017). "Underwater Noise from Large Commercial Ships – International Collaboration for Noise Reduction" in *Encyclopedia of Maritime and Offshore Engineering*, John Wiley & Sons, Hoboken, New Jersey, 1–9. https://doi.org/10.1002/9781118476406.emoe056.

Spence, J.H., Fischer, R.W. (2016). Requirements for reducing underwater noise from ships, *IEEE Journal of*

Oceanic Engineering **42(2)**, 388–398. https://doi.org/10.1109/JOE.2016.2578198.

Strietman, W.J., Michels, R., Leemans, E. (2018). *Measures to reduce underwater noise and beach litter, An assessment of potential additional measures for the Netherlands*. Wageningen Economic Research, Hague, 38 p.

TNO (2016). Second Acoustic underwater measurements BLUE Pilling. TNO, Haag, Report R10567.

Trevorrow, M.V., Vasiliev B. (2008). Directionality and maneuvering effects on a surface ship underwater acoustic signature, *Journal of the Acoustical Society of America* **124(2)**, 767–778. https://doi.org/10.1121/1.2939128.

Turner, A.E. (1969). The use of damping materials for noise reduction on a passenger ship, *Journal of Sound Vibration* **10(2)**, 187–197.

Vakili, S.V., Ölçer, A.I., Ballini, F. (2020). The development of a policy framework to mitigate underwater noise pollution from commercial vessels: The role of ports, *Marine Policy* **120**. https://doi.org/10.1016/j.marpol.2020.104132.

Veirs, S., Veirs, V., Wood, J.D. (2016). Ship noise extends to frequencies used for echolocation by endangered killer whales, *Peer J* **4(e1657)**. https://doi.org/10.7717/peerj.1657.

Weilgart, L. (2023). *Best Available Technology (BAT) and Best Environmental Practice (BEP) for Mitigating Three Noise Sources: Shipping, Seismic Airgun Surveys, and Pile Driving*. Convention on the Conservation of Migratory Species of Wild Animals (CMS), Bonn, 53 p.

ZoBell, V.M., Frasier, K.E., Morten, J.A., Hastings, S.P., Peavey Reeves, L.E., Wiggins, S.M., Hildebrand, J.A. (2021). Underwater noise mitigation in the Santa Barbara Channel through incentive-based vessel speed reduction, *Scientific Reports* **11(18391)**. https://doi.org/10.1038/s41598-021-96506-1.