Raise the Shields: Protecting Marine Animals from Underwater Explosions, Illustrated by Noise Abatement Modeling

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Abstract

Underwater detonations, whether from unexploded ordnance (UXO) clearance or new munitions, produce intense, impulsive sound that can lead to hearing impairment and cause injuries, including those leading to mortality of marine animals. Despite these risks, noise abatement systems are not routinely applied, and one of the aims of this study is to demonstrate the need and potential effectiveness of implementing them. This chapter summarizes the issue of underwater detonations, their effects on the marine fauna, and available mitigation strategies. A case

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study for the Gdańsk Bay, Baltic Sea, used sound propagation modeling to assess the potential impacts for two explosive charge sizes (10 kg and 250 g TNT equivalent), without and with the application of a big bubble curtain (BBC) as noise abatement. Modeling results showed that temporary threshold shifts in harbor porpoises occurred within the largest affected area, while physical injury to fish was limited to the smallest affected area. The application of a BBC heavily reduced the impact ranges across the considered species, demonstrating near-complete mitigation of the evaluated risks. The results highlight the value of integrating sound-propagation modeling into UXO clearance planning and support the routine application of noise abatement systems to minimize hazards, particularly for species already threatened by other pressures, such as the harbor porpoises in the Baltic Sea.

Keywords

Unexploded ordnance · UXO · Underwater explosion · Noise abatement · Big bubble curtain · Harbor porpoise · Sound modeling · Underwater sound

Introduction

Legacy munitions from past wars pose a significant and persistent threat to the marine environment, human safety, and offshore infrastructure due to their explosive potential and the release of toxic chemicals. In some cases, on-site detonation is the only available disposal method, releasing high acoustic energy into the water environment. Although the explosion is usually a short and single event, it can be lethal to exposed animals. It is estimated that hundreds of thousands of unexploded ordnance (UXO) residues remain on the seabed of the Baltic and North Seas, and a small portion of them are regularly cleared underwater through detonation. In addition, the detonation of new ammunition also poses a problem.

Despite the detrimental consequences of underwater detonations for marine animals, noise abatement measures are not routinely implemented in many regions, with Germany being an example of recent implementation. This chapter aims to summarize and present the issue of underwater explosive detonations, their effects on marine animals, and the available mitigation measures, with a particular focus on UXO. To demonstrate the influence of the noise abatement system, a case study applying numerical noise modeling was conducted.

Underwater Explosions and Underwater Noise

Underwater explosions release energy through rapid chemical reactions, resulting in a rise in temperature and the formation of high-pressure gases, followed by the generation of a shock wave and the subsequent creation of a gas bubble (Kiciński and Szturomski 2020). The initial, nearly instantaneous increase in pressure is referred to as a shock wave (Dall'Osto et al. 2023). As the shock wave propagates spherically outward, its pressure decays as the gases expand, forming a bubble (Matos et al. 2024). During this process, the shock wave loses its initial velocity as the pressure decreases ($v \approx 5000$–8000 m/s) and continues to travel at the speed of sound in water ($c_0 \approx 1500$ m/s). This complex phenomenon involves both sound generation and propagation (Kiciński and Szturomski 2020). A portion of the energy initially released by the blast eventually propagates through the water as sound. This sound exhibits a rapid onset and decay, high amplitude, and short duration, and is thus categorized as impulsive (NMFS 2024a). Sound levels increase with the size of the charge and decrease with distance from the detonation site (Bellmann et al. 2024).

For new ammunition, the sound levels depend on the size of the charge, while for UXO, the sound correlates only with the ignition (primary) charge since munitions submerged for decades are mostly not fully ignitable (Bellmann et al. 2024; Lepper et al. 2024).

Underwater detonations can occur as high-order events, in which the original explosive fully detonates together with the attached donor charge, or as low-order events, where the old munition does not reach its full explosive yield. New munitions typically undergo high-order detonation, whereas UXO clearance can use either method, with low-order detonations generally using smaller charges, for example, 250 g TNT (Lepper et al. 2024; Bellmann et al. 2024). Low-order detonations generate substantially lower sound levels than high-order detonations. Deflagration, an alternative low-order technique, can reduce sound by roughly 20 dB compared to high-order detonation (Lepper et al. 2024).

In deflagration, a small, shaped charge penetrates the old explosive and causes it to burn without a full detonation. Since not all the explosive material may be consumed and fragments of the casing can remain, the release of toxic substances can be higher than in high-order detonations and must be considered (Bellmann et al. 2024; Lepper et al. 2024). Although sound levels are lower, the noise generated by deflagration can still affect marine life, making mitigation measures necessary (Lepper et al. 2024). Implementing appropriate measures for both high- and low-order detonations can reduce noise-related risks to marine fauna. It can also potentially help minimize chemical hazards by allowing high-order detonations, which might potentially enable complete on-site munition destruction while managing sound-related risks (Bellmann et al. 2024).

Effects of Underwater Explosions on Marine Animals

Underwater explosions can cause physiological, auditory, and behavioral effects in marine animals. The severity of effects generally tends to increase with sound intensity and proximity to the source, with effects and thresholds varying across species, body size, mass, and depth at which the animal is located.

Physiological effects usually result from shock waves, cavitation, and the sudden pressure changes associated with them. These can cause barotrauma in marine mammals and fishes, leading to blast injuries such as hemorrhages and organ damage, including the inner ear and lungs, which are often fatal. In fishes, swim bladder injuries may also occur (Bowman et al. 2024).

Auditory effects include auditory injury (Aud Inj), temporary threshold shift (TTS), and permanent threshold shift (PTS). Aud Inj refers to damage to inner ear structures affecting hearing and may lead to PTS, although it does not always result in permanent threshold shifts. PTS is an irreversible elevation of hearing thresholds at a given frequency, whereas TTS is reversible (NMFS 2024a). TTS can occur in both marine mammals and fishes, although it has not been directly measured in fishes following explosive exposure (Popper et al. 2014). However, reduced inner ear sensory hair cell density has been observed in fishes after explosions, with severity decreasing with distance from the source (Bowman et al. 2024). Fishes can regrow these cells and are generally not susceptible to PTS, unlike marine mammals. Even temporary hearing impairment can potentially reduce the fitness of marine animals as they rely on hearing for orientation, foraging, predator detection, and more.

This can be particularly detrimental for species such as the harbor porpoise, critically endangered in the Baltic Sea, which rely on very high-frequency echolocation to detect prey and avoid obstacles. Any reduction in hearing sensitivity at ecologically relevant frequencies could have serious consequences for their survival (Kastelein et al. 2020; von Benda-Beckmann et al. 2015).

Behavioral effects include avoidance, behavior modification, startle reactions, and a stress response. The latter reflects both physiological and behavioral responses. Data on wild fish behavior are limited, but startle responses are likely (Popper et al. 2014).

Field data illustrate the severity and scale of these risks. Von Benda-Beckmann et al. (2015) estimated that 88 underwater blasts in a single year could have caused approximately 1280–5450 permanent hearing impairments, including partial hearing losses, in harbor porpoises. In 2019, the clearance of 42 World War II mines by NATO in the Fehmarn Belt Marine Protected Area (Baltic Sea, Germany) was followed by several harbor porpoises found dead on the shore with injuries indicative of blast exposure (Siebert et al. 2022). This instance is a real example of the severity of the danger of underwater detonations, including UXO clearance and is a call for mitigation measures.

Mitigation Measures for Underwater Detonations

To minimize potential negative effects on marine animals during detonations, in case they cannot be avoided, two main approaches can be applied: (1) deterring animals from the area and (2) noise abatement measures, such as installing bubble curtains. In addition, operations should be timed to avoid the most sensitive periods for marine animals, particularly for already vulnerable and protected species, such as fish spawning seasons, harbor porpoise breeding, calving, and nursing periods, as well as seal breeding and pupping seasons.

Deterrence methods include acoustic devices such as seal scarers, pingers, and small targeted deterrent blasts (≤150 g) conducted before the main detonation. However, these methods can themselves pose risks to animals, and for this reason, deterrent blasts are prohibited in some regions, for example, Germany (Bellmann et al.

2024). Other suggested measures include the use of four fast motorboats circling concentrically outward from the center of the deterrence area and two vessels traversing the area with active sonar systems operating. Indirect measures involve marine observers, who notify the command upon sighting a marine mammal, prompting suspension of detonation activities (Górski et al. 2020). Nevertheless, deterrent measures may not be sufficient alone (Siebert et al. 2022) and do not address the source of the problem, namely, the high acoustic pressures generated by the detonation.

A very effective method for mitigating sound exposure from underwater blasting is the use of single or double big bubble curtains (BBCs) (Bellmann et al. 2024; Strehse et al. 2023). A bubble curtain is created by releasing pressurized air through a weighted pipe or nozzle placed on the sea floor, forming a continuous ring of bubbles that rise to the sea surface, encircling the detonation (Strehse et al. 2023).

A bubble curtain reduces pressure through the compression and expansion of bubbles in response to the pressure wave. Compression converts sound energy into heat, partially absorbed by the surrounding water, while expansion generates rarefaction waves. These effects lower the pressure peak, spread the energy over time, and reflect some sound back toward the detonation site (Strehse et al. 2023).

The bubble curtain radius must be substantially larger than the gas bubble generated by the explosion, if it is too small, expanding water and gas can disrupt the curtain. Consequently, the curtain radius must increase with the explosive charge weight. The application of bubble curtains in deep waters can be challenging. As an alternative, tunable acoustic resonator systems could be used (Wochner et al. 2017; Wochner, personal communication).

Modeling Scenario for Underwater Explosions in Gdańsk Bay, Baltic Sea, Poland

To assess the extent of the potential effects of underwater explosions on marine animals, a sound propagation model was applied, and a risk assessment was performed. A site in Gdańsk Bay, Baltic Sea, Poland, with a high likelihood of old munitions residuals, was selected for a realistic scenario (Fig. 1). The timing was chosen to avoid the most sensitive periods for local fishes (e.g., Atlantic herring, Atlantic cod, garfish), seals (gray seal, harbor seal), and harbor porpoises. Thus, the model was set up to represent the Baltic Sea conditions in October, including water temperature and pH. The depth at the chosen location was approximately 40 m.

Two detonation charge sizes (10 kg and 250 g TNT equivalent) were considered to illustrate the range of potential effects. The respective source spectra were derived with the approach described by Urick (1971). The sound propagation was modeled with the Underwater Acoustic Simulator (UAS) (DHI 2024), which is based on the Parabolic Equations developed by Collins (1993). For each charge, an unmitigated and a mitigated scenario were evaluated. As a mitigation measure, the measured insertion loss of a single BBC shown by Bellmann et al. 2024 is subtracted from the results derived for the unmitigated case. The computed unweighted sound exposure levels derived in this study are in the range of measured values reported in the literature (Bellmann et al. 2024; Lepper et al. 2024). The impacts evaluated included Aud Inj and TTS for harbor porpoises and seals, and the Onset of physical injury for fishes, according to the NMFS criteria (NMFS 2024b, c).

The largest maximum impact range was observed for TTS in harbor porpoises, with the 10 kg charge producing effects extending outside the bay (Fig. 1) and reaching up to approximately 73 km from the detonation site (Table 1). The second-largest impact range was Aud Inj in harbor porpoises, occurring in both the 10 kg and 250 g unmitigated scenarios. The smallest impact range was observed for physical injury in fish (Table 1).

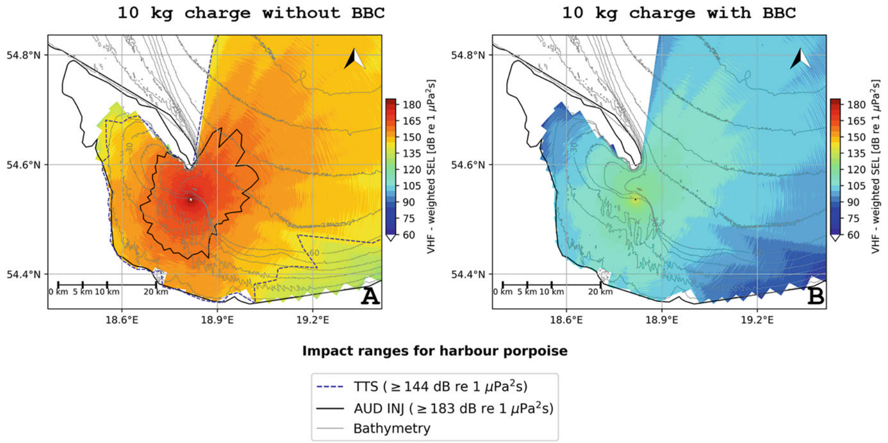

Fig. 1 Impact areas of selected effects of a 10 kg underwater detonation on harbor porpoises under unmitigated conditions (**a**) and with a single bubble curtain (**b**)

Table 1 Maximum impact ranges (km) of the selected effects of underwater detonations on selected marine animals for two charge sizes (10 kg and 250 g) under unmitigated conditions and with a single bubble curtain

		No mitigation		With BBC	
		10 kg charge	250 g charge	10 kg charge	250 g charge
Species	Effect[a]	Maximum Impact range (km)			
Harbor porpoise	Aud Inj	17.05	1.6	0.05	0.05
	TTS	73.3	12.3		
Gray seal, harbor seal	Aud Inj	1.65	0.05		
	TTS	15.45	1.15		
Fishes (e.g., Atlantic herring, Atlantic cod)	Onset of physical injury (≥2 g)	1.45	0.05	0.03	

[a]Thresholds applied (dB re 1 μPa^2·s, SEL):
Harbor porpoise (VHF-weighted): Aud Inj 159, TTS 144
Gray seal/harbor seal (PW-weighted): Aud Inj 183, TTS 168 (NMFS 2024b)
Fishes (nonweighted SEL): onset of physical injury (≥2 g) 187 (NMFS 2024c)

The difference between the 10 kg and 250 g scenarios was substantial, with the smaller charge producing shorter impact ranges across all species and types of effects. For both charges, the application of mitigation measures further reduced these distances. The BBC achieved nearly a 100% reduction in the modeled impact ranges, leaving almost no detectable impacts for the considered effects. For the 10 kg charge, the TTS impact range in harbor porpoises was reduced by approximately 1466-fold with the BBC mitigation (Table 1).

Conclusions and Recommendations

Underwater detonations generate intense, impulsive sound that poses clear risks to marine animals. Although the magnitude of these risks depends on the local propagation conditions, charge size, and detonation type, even reduced-noise techniques such as low-order detonations, including deflagration, do not generally eliminate the need for noise abatement.

The presented modeling case study, conducted for two different charge weights in the Bay of Gdańsk, Baltic Sea, Poland, demonstrates how the impact ranges from underwater detonations can be assessed. The modeled impact areas extend over considerable distances, particularly affecting species that are sensitive to very high-frequency sound, such as the harbor porpoise. Even comparatively small charges can produce large-scale effects. The results also show that applying a bubble curtain can reduce these ranges by nearly 100%, effectively preventing most auditory and physical injury risks considered in the examined modeling scenarios.

These findings illustrate the practical value of the modeling approach to assess the influence of noise abatement measures prior to UXO-clearance operations. Such modeling allows operators and authorities to anticipate the scale of negative effects, assess charge-size options, and design effective mitigation strategies before operations begin.

Given the ongoing need for UXO disposal, the routine implementation of noise abatement, supported by site-specific modeling, should be considered standard practice, particularly in the Baltic Sea, where the harbor porpoise is critically endangered. Consistent operational requirements and clear regulatory guidance would help ensure that often unavoidable detonations of UXO can proceed while substantially reducing harm to marine life.

Competing Interest Declaration The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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