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Comprehensive review on principles and practices of underwater drilling and blasting, its environmental impacts, and mitigation techniques

AMAR PRAKASH KAUSHIK[1,*], VIVEK KUMAR HIMANSHU[1], M P ROY[1], A K MISHRA[1], ASHISH MISHRA[2] and HUZAIFA SUFIYAN SIDDIQUE[3]

[1]Department of Rock Excavation Engineering, CSIR – Central Institute of Mining & Fuel Research, Dhanbad 826001, India
[2]The Andra Pradesh Mineral Development Corporation Limited, Vijayawada 521137, India
[3]Maharana Pratap University of Agriculture and Technology (M.P.U.A.T.), Udaipur 313001, India
e-mail: amar96cimfr@gmail.com

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Abstract. Underwater drilling and blasting techniques have been developed to overcome the challenges posed by various subaquatic operations, including marine construction, oil and gas exploration, and underwater mining, demolition, dredging and excavation, seismic surveys and marine research. The drilling operation is followed by underwater blasting, which involves the creation of boreholes in submerged surfaces, such as sea beds or riverbeds. Specialized drilling equipment is utilized, which can operate in aquatic environments. To ensure efficient and reliable performance, the drilling equipment is designed to withstand the pressures and corrosive nature of seawater. Once the desired depth is reached, underwater blasting is utilized to break the rock or seabed. The primary objective of blasting is to loosen the substrate and create a cavity for subsequent operations. Safety is a crucial factor in underwater drilling and blasting operations. To safeguard personnel involved and prevent accidents during drilling and blasting activities, strict safety measures are implemented. In addition to human safety, precautions are taken to minimize the environmental impacts of underwater drilling and blasting, including measures to prevent pollution, protect marine life, and preserve the underwater ecosystem. In this article, the core elements of underwater drilling and blasting operations are outlined. Despite notable progress in this domain, the paper highlights the enduring constraints and obstacles, underscoring the need for continued investigation and understanding.

Keywords. UDB—underwater drilling and blasting; environmental impacts; ground vibration; underwater shockwaves; air-bubble curtain.

1. An introduction to underwater blasting

Maritime trade is a fundamental pillar of a nation's economy, enabling the movement of goods, fostering economic growth, and promoting global trade relationships. Ports and harbors play a pivotal role in facilitating this trade, serving as critical points of connection between land and sea transportation. Ports are deepened by mechanical means or by blasting. In mechanical dredging, sediment is taken out of a water body, transported, and deposited at a distant location [1–3]. Dredging is extremely challenging when there are hard or complex rock formations [4]. In that scenario, underwater blasting can precisely fragment rock masses into sizes that are conducive to dredging [5]. Underwater Drilling and Blasting (UDB) has a wide range of applications such as structural rehabilitation, geophysical exploration, levee removal, deepening of channels and harbors, emergency levee construction during extreme floods, digging trenches for laying oil and gas pipelines and underwater communication cables, etc. [5, 6]. Underwater blasting is similar to surface blasting, where rocks are broken under the influence of shock waves and gases [7]. The operational process of underwater blasting is a lot more complicated and time-consuming than surface blasting. The methods for underwater blasting are outlined below:

- Drilling and blasting with divers inside water [7].
- Drilling and blasting from Surface using a buoyant pontoon/platform [5].
- UDB by filling the neighbouring area of excavation site [7].

*For correspondence

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The method of underwater blasting, though similar to surface blasting, faces unique challenges due to limited space for execution. Unlike surface blasting that offers ample room for machinery movement, maintenance, and operation, underwater blasting lacks natural working space for machine installation. All essential working units, from drilling machines to workshops and power supply units, need to be equipped on a floating pontoon due to the constraints of the underwater environment [5]. This installation process is both time-consuming and intricate, demanding a higher level of precision, accuracy, and expertise.

However, despite these challenges, underwater blasting holds immense economic benefits for the nation. Maritime transportation, a crucial component supporting trade and economic progress, heavily relies on the effective functioning of ports, harbors, and channels [8]. These integrated elements collaborate to ensure the efficient and timely transit of goods, promoting trade alliances and economic advancement. Underwater drilling and blasting play a critical role in the construction and enhancement of these crucial infrastructures. As a result, this technique indirectly benefits the nation's economy. Let us investigate in more detail how these structures offer advantages for the nation's economic development.

Construction of Ports Ports play a crucial role in global trade, commerce, and industry, serving as vital hubs facilitating the movement of goods across countries and continents. Efficient ports contribute to economic growth and prosperity by streamlining the supply chain, reducing transit time, and lowering logistics costs [9].

Deepening of Ports Insufficient ports can impede the circular system of container shipping, reducing capacity and increasing costs [10]. Improving container port performance lowers trade costs, enhances resilience, and reduces unnecessary emissions from vessels. The economy of scale illustrates the present tendency of shipping companies to build larger ships to reduce operational costs. With the increase in ship sizes and container sizes, foreign currency income also rises. It is anticipated that deep ports will significantly increase foreign currency income and contribute to the GDP [11].

Deepening of Harbors and Channels Narrow, shallow channels, and harbors incur high costs in terms of delays and productivity. These challenges lead to increased costs for businesses due to extended time and out-of-pocket expenses, such as higher labour costs and inventory delays associated with shipping [12]. This situation makes products and services more expensive and less competitive or affordable, especially in the export market. Fragmentation of hard rock formations through Underwater drilling and blasting is a common method to deepen channels and harbors, allowing for the accommodation of larger vessels [5]. This approach mitigates the challenges posed by shallow or narrow waterways.

2. Principles of underwater blasting

Underwater rock blasting and surface blasting differ primarily in the environment they interact with water and air, respectively [13]. One significant difference is the acoustic impedance, which is a measure of how sound travels through a medium [14, 15]. Water has a much higher acoustic impedance compared to air [16]. Secondly, we must consider the effects of varying water depths on the strength of the rock material. In deeper waters, the pressure can enhance the rocks' resistance to tensile failure [15, 17]. However, when it comes to the propulsion of broken blocks, a significant contrast is observed in the resistance they encounter during underwater and surface blasting [6, 15]. This difference is due to the substantial disparity in viscosity between water and air [15]. Previous studies have consistently found that water occupies the blast holes during underwater blasting [18, 19]. This presence of water in the holes acts as a buffer against the direct impact of detonation waves on the rock hole walls [15, 19]. Prior to the stress waves from the blast reaching the boundary between rock and water, the way the rock breaks is similar to what happens in surface blasting [19, 20]. Once the blast holes are triggered, the blast wave expands in a cylindrical shape, exerting pressure on the water as it travels [19]. This wave then forcefully hits the nearby rock's surface through the thin layer of water, causing the disintegration of the rocks' intergranular structure at some distance from the blast hole [7, 21, 22]. The intensity of the energized wave within the rock significantly exceeds the rock's ability to withstand compression, resulting in a compressional failure of the surrounding rock [23]. The impact of this high-intensity shockwave is forceful, ultimately crushing the solid rock [24]. When the waves travel further, the powerful detonation wave weakens, transforming into a low—intensity stress wave [22]. The detonation wave applies pressure to the blast holes in a radial fashion, resulting in tensile deformation of the surrounding rock in the tangential direction [19]. Rocks typically possess a limited tensile strength, usually about 0.02 to 0.10 times their strength against compression [25]. When the tangential stress on the surrounding rock reaches its maximum tensile strength, the rock breaks in that tangential direction, forming cracks that extend radially and are connected to crushed areas [19].

When stress waves from the blast reach the boundary where rock meets water, they undergo reflection and transmission on the interface [16]. This results in not only compressional waves being transmitted to the water but also reflected tensile waves appearing in the rock mass [15]. This mechanism is different from surface blasting, where almost all incident waves are reflected to form tensile waves [7]. The amount of energy carried by the reflected wave is influenced by the compression wave's strength. Fracturing is primarily a result of the tensile waves that bounce back. In underwater blasting, since not all compression waves are reflected, the fracturing caused by the reflected tensile waves is less compared to surface blasting. In Liu's experiments, a comparison was made between blasting effects on land and underwater using concrete samples [18]. The results revealed that to achieve the same impact as surface blasting, the amount of explosives needed for underwater blasting at a 25-meter water depth had to be increased by two to four times [18]. Zhao highlighted that the most affected factor in underwater blasting is the throw distance [26]. When the water depth goes beyond 6 meters, rocks blasted underwater do not project beyond the water surface, significantly reducing their propulsion compared to surface blasting [26]. Figure 1 depicts a schematic diagram illustrating the mechanism of underwater blasting.

3. Drilling system for underwater blasting

The drilling system for underwater blasting comprises of drilling machines, anchoring systems, casing and drilling units equipped over platforms. Over the years, various developments have occurred in these systems to address the challenges of drilling. These developments have been discussed in various subsequent sections. A schematic of different drilling systems for underwater blasting along with their advancement sequence is shown in figure 2.

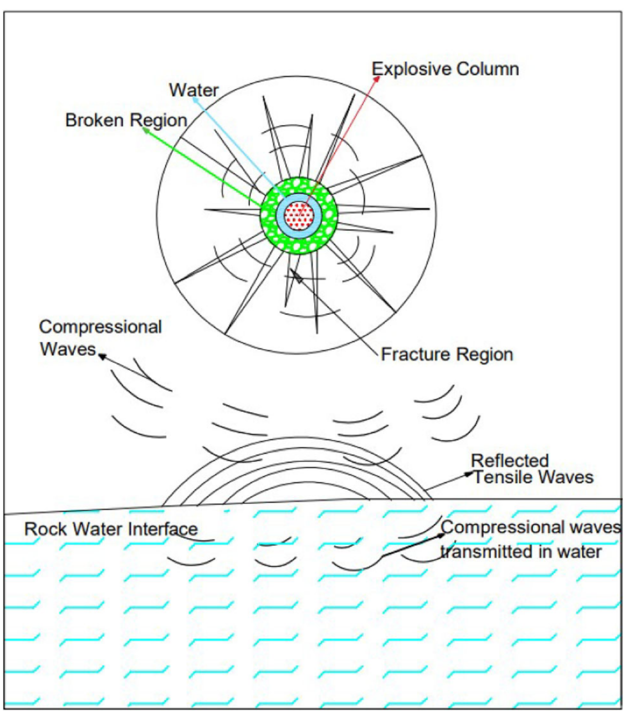

Figure 1. Mechanism of Underwater Blasting [15, 19]

3.1 *Drilling machines used in underwater blasting*

Drilling in underwater blasting is carried out using a specially designed platform called pontoons [5, 27]. Design of the pontoons also impacts the blast design parameters such as spacing, burden, number of holes, and rows. In underwater blasting, there are three primary drilling methods. They are Top hammer, Down the hole (DTH) and Rotary drilling. In Top Hammer drilling, the percussive force of the hammer is applied directly on the drill rod, which is transmitted to the drill bit through the rod. While travelling down the length of the drill rod, the impact energy of the hammer is attenuated due to the buckling effect [7]. This problem can be controlled with downhole drilling. In this case, the impact energy of the hammer is transmitted directly to the drill bit. As a result, energy loss in DTH is declined significantly, and it is considered very effective in hard rock excavation [7]. DTH generates less noise hence, it is considered the most advantageous and accurate drilling method. The use of rotary drilling allows for greater depth of drilling [7]. This method requires large machinery units and huge capital investment [7]. This reason prevents its applicability under shallow depth of cover.

3.2 *Pontoons and its anchoring technique*

Pontoons, essential platforms for underwater drilling, play a critical role in rock mass drilling at greater depths of cover. When the excavation depth remains under four meters, the optimal approach involves filling the targeted area with rock material. Subsequently, holes are drilled and effectively blasted through the filling for excavation purposes [7]. However, if the depth surpasses four meters, the drilling and charging activities take place from pontoons or barges floating and anchored into the sea bed [7]. Notably, for anchoring the platform at shallow depths, two or four spuds are typically employed [5, 7, 28]. In situations where the vessel lacks spuds, secure anchoring is achieved by linking the vessel to the coast using wire ropes and winches, tug boats, or a combination of wire rope with tug boats or spuds [28].

Pontoons are the airtight hollow structures. It is equipped with the standard stainless-steel fittings, conduits and pipes for electricity and water supply. It is designed to provide buoyancy in water. Pontoons float easily in water and provide necessary space for mounting and installation of the drilling equipment. Pontoons consist of drill towers, anchor, winches, compressors, generator, accommodation such as offices, mess, workshop, explosive storage room, etc.

Ocean current and waves do not provide stability to the pontoons. In this condition, drilling is very difficult and there are chances of hole deviation. Hence, it is important to provide stability to the pontoons for easier and faster rate of drilling. Spud anchoring is the most

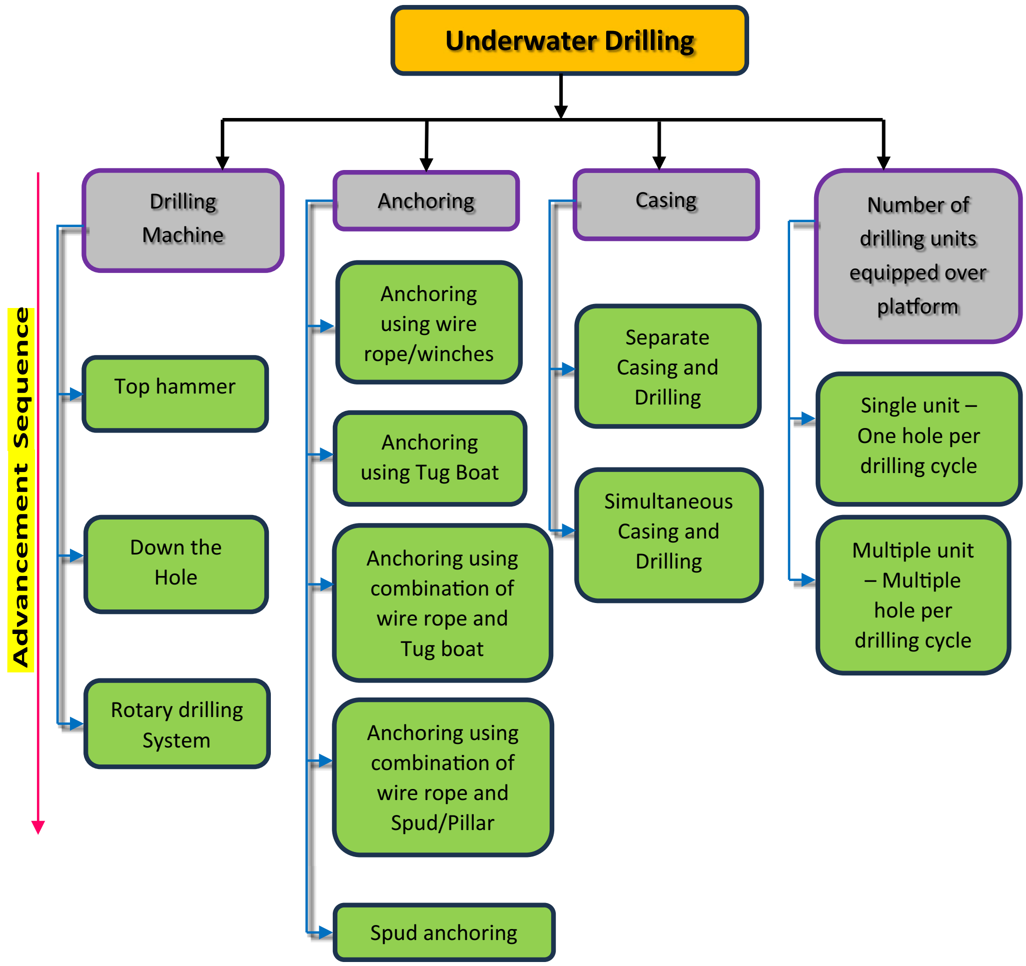

Figure 2. Sequence of advancements in Underwater drilling system

acceptable anchoring technique used for the stability of pontoons. Spuds are the pillars which move vertically inside the anti-frictional guide rollers attached to the pontoon [29]. Vertical movement of spuds is carried over winding drum which is operated by the spud engine [30]. The pillars are lowered and grounded into the sea bed for delivering firmness to platforms. When pillars are properly anchored into sea bed, the pontoons are entirely lifted out of seabed by 80 cm to position the self-elevating pontoon [31]. A schematic diagram of pontoon with spud anchoring technique is shown in figure 3.

3.3 *Drilling operation for underwater blasting*

Drilling in underwater blasting is done with the help of drill rigs. The drill rigs are the complex equipment that is used to penetrate the surface of the Earth's crust. The number of drilling rigs equipped on the floating pontoons depends on the size of platform, capital investment and area supposed to be excavated, etc.

Drilling rig is mounted on individual mobile frame, which travels on guide rail attached to the platform. Rollers facilitate the movement of drilling rigs on the guide rail. Drilling is faster, if the number of drill rigs equipped on the platform is equal to the number of holes planned in a row. Once the first row is drilled, the pontoon is shifted for drilling successive rows.

If the drilling rigs equipped on the platform are limited due to capital constraints. Then the same drilling rig is moved from one end to the other on guide rails to drill all the holes planned in a row. The next row is drilled by shifting the pontoon by distance equal to predetermined burden between the rows. With single drilling unit, the method is time consuming and requires more precision to maintain the correct distance between holes.

Underwater drilling from floating pontoon is advantageous in many aspects. Some of the major advantages of this technique are as follows:

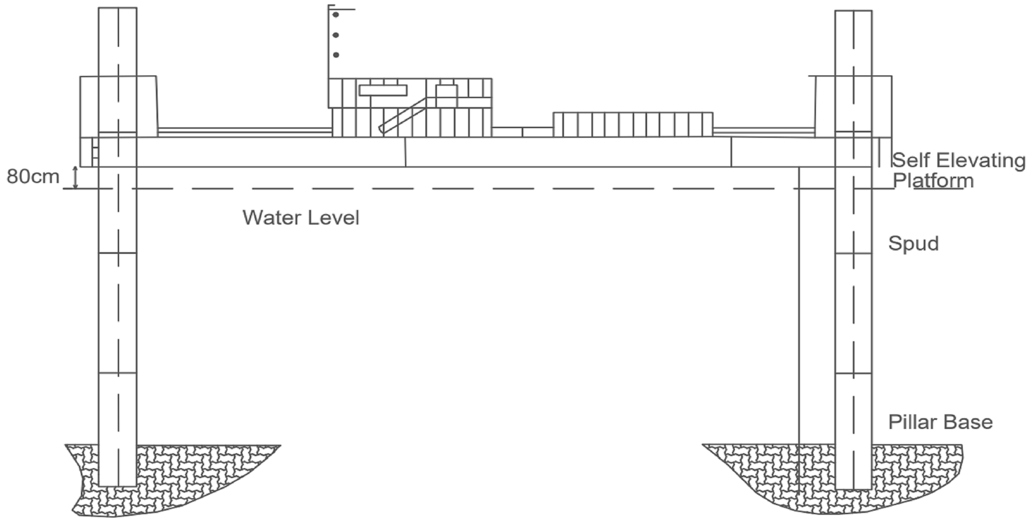

Figure 3. Schematic diagram of pontoons with spud anchoring [7]

- Drilling and loading of explosives in the blast hole from the floating pontoons is safe and easier.
- The visibility in the water does not affects the work.
- It reduces the costs because of fewer diver hours [7].

3.4 *Blast hole casing*

Casing is an essential component to prevent silt and sand from infiltrating the boreholes. Certain manufacturers offer drilling rig equipped with a valuable feature, known as ODEX drilling (an Atlas Copco product), which enables the simultaneous drilling and casing of deep holes across diverse geological formations [7, 33]. These drilling rigs incorporate an eccentric retrievable drilling system consisting of a pilot bit and a reamer "wing." As the drill bit penetrates through the strata, the specially designed "wing" unfurls and functions as a reamer [32, 33]. This process generates additional space for the casing pipe to progress. As the pilot bit advances, once the casing attains stability, the reamer wing is paused and retracted back into the pilot bit [32, 33].

In ODEX drilling, a portion of the impact force is conveyed through the shoulder of the guiding device into the casing pipe, striking a specialized casing shoe situated at the lower extremity of the casing [34]. Consequently, the entire drill string can be extracted from within the casing, firmly securing the casing within the rock [27, 33, 34, 36]. Subsequently, traditional drill strings can be employed to continue drilling into the rock bed [27, 33]. The casing material comprises standard steel tubes available in commercial dimensions [34]. The coupling arrangement for drill rods and casing pipes is automated for smaller rigs and managed manually for larger rigs [5].

4. Blasting and explosives

Drilling in underwater blasting is very complex, it requires precision to maintain the accurate blast design pattern. Drilling and charging of holes are done simultaneously to avoid blocking of shot holes by silt and sand. The work is done with utmost care to save time and cost. Slurry or emulsion cartridge are primarily used for charging the shot holes. These explosives are water resistant but their performance is reduced underwater. They are not able to withstand hydrostatic pressure for longer period. To improve the underwater performance of slurry and emulsion explosives, coupled plastic tube explosives have been developed as shown in figure 4. They are made up of special plastic which can withstand the hydrostatic pressure. They have cap sensitive, high strength, high VOD, and excellent water resistance properties. These plastic tubes have positive screw coupling arrangement which gives flexibility for varying the quantity of explosive in shot

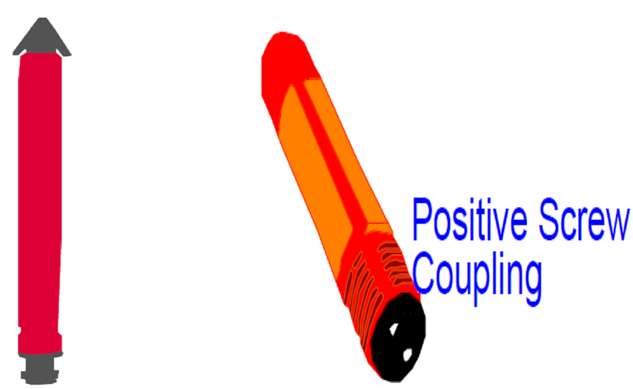

Figure 4. Couplable plastic tube explosive [35]

holes. They can withstand the hydrostatic pressure up to a depth of 60 m [35]. These explosives are detonated with No. 8 strength detonator [35].

Once charging of hole is completed, the outer casing is raised to allow the slip ring attached to the hemp rope to drop into the water adjacent to the casing pipe [36]. The slip ring is raised to recover the lead wire of the detonators. Finally, rings are pulled upward to sea surface and tied with the floaters. When charging is complete, divers descend into the water to connect inter hole and inter row delays. Before firing the shot holes, the pontoon is shifted to a safe place. A schematic diagram illustrating the charging of the blast holes is shown in figure 5.

4.1 *Selection of explosives*

Selecting the appropriate underwater explosive for blasting is a critical process that involves considering several important factors. These factors are crucial for ensuring the safety, effectiveness, and precision of the blasting operation. Here are the key factors and their importance in choosing the right underwater explosive:

- *Velocity of Detonation* The velocity of detonation is crucial for efficient blasting. A higher detonation velocity ensures that the explosive effectively breaks and displaces the surrounding material, creating the desired blast effect underwater [5].
- *Density* Proper density of the explosive is important to ensure it can overcome any issues related to muddy or slushy conditions at the bottom of the drill holes. A denser explosive can penetrate and displace the surrounding material effectively [5].
- *Detonation stability* The stability of the explosive's detonation is crucial for safety and predictability during the blasting process. An explosive with good detonation stability ensures a controlled and reliable detonation, minimizing risks associated with unpredictability [5].
- *Water-resistance and shelf life* An explosive with high water resistance is essential for maintaining its effectiveness underwater and ensuring it does not degrade or become inert when exposed to water. Additionally, a good shelf life is important to maintain the explosive's efficacy over time and during storage [5, 37].
- *Bulk strength* Having higher bulk strength is important as it maximizes the effectiveness of each blast hole, ensuring efficient fracturing and displacement of the material [6].
- *Sensitivity under hydrostatic pressure* The explosive must maintain its sensitivity even when subjected to high hydrostatic pressure underwater. This ensures that the explosive remains effective at the intended depth of the blast [6].

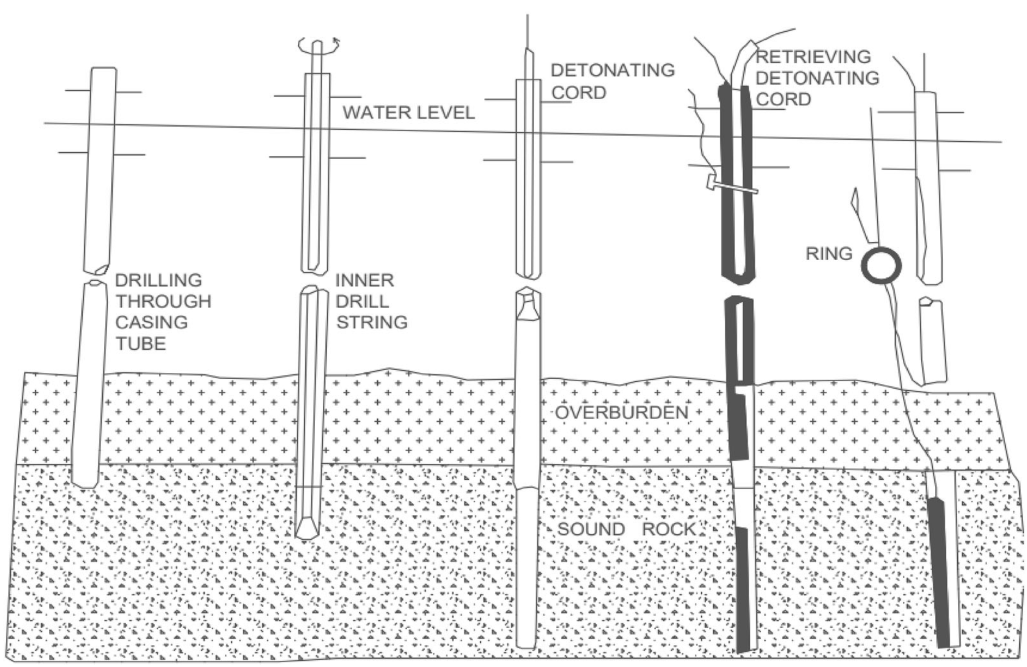

Figure 5. Charging of the blast holes [7]

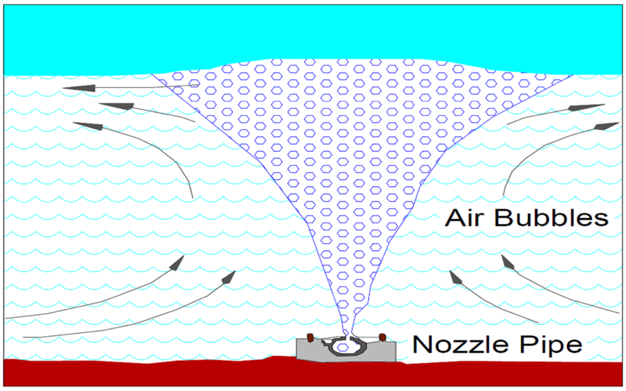

Figure 6. Air bubble curtain and perforated steel pipes arrangement [56]

In summary, an ideal underwater explosive need to balance these factors to ensure safe, effective, and predictable blasting operations in underwater environments.

5. Adverse impacts of underwater drilling and blasting

In the past few decades, there has been a significant increase in underwater anthropogenic activities, including the extraction of oil and natural gases, blasting, extraction of rare earth minerals, and underwater civil construction work. Regrettably, these activities have detrimental effects on the aquatic ecosystem, leading to an escalation in noise levels, vibrations, and shock waves. Organizations at the national and international levels are deeply concerned about the impacts of these underwater activities and are actively seeking ways to mitigate them. Some of the major adverse impacts of underwater drilling and blasting (UDB) have been outlined below:

- *Noise* Equipment used for underwater excavation continuously vibrates and generates noise. Intensity of the noise created by machinery is more in comparison to the drill bits penetrating the sea floor [38]. Noise and vibration generated from the machinery travel down the spud and penetrate into water. These sound waves travel underwater where they superimpose with each other and increase the noise level.
- *Ground vibrations* The most undesirable effects associated with Underwater blasting are ground vibration and shock waves. Ground vibration leads to the instability of movable and immovable structures. The level of influence depends upon the intensity of ground vibration. The impact of vibration can be minimized by devising the controlled blasting technique.
- *Underwater shockwaves* Shockwaves adversely impact aquatic flora and fauna, and vessels underwater. The intensity of unconfined shock waves is 10 to 15% higher than the intensity of in-hole shock waves [7]. The velocity of underwater shockwaves decreases with the increase in distance from the blast location [7]. It reduces till the velocity of shockwaves become equal to the speed of sound in water (1435 m/s) [7].
- *Impacts on aquatic Flora and Fauna* Underwater blasting causes immense destruction to the aquatic flora and fauna (Biota and Benthos) thriving in the vicinity of excavation [39–44]. The invisibility of the excavation site is the biggest constraint in underwater blasting. The dredging operator operates the machine on his own assumption to remove the blasting material. The lack of visibility could not limit the swing angle of the dredger, causing damage to biota and benthos [46–48].

Phytoplankton—is the foundation of the aquatic food web, the primary producers, feeding everything from microscopic, animal-like zooplankton to multi-ton whales. It is the main link in the energy transmission at the secondary level. They play a considerable role in the production potency of any aquatic system. Primary consumers (crustaceans, zooplankton and small fish) are dependent on phytoplankton for their survival. Higher groups such as large fish and whales feed primary consumers in the tropic level. Humans feed on every level of this food chain [39–54]. UDB disturb this food chain by two consecutive actions, i.e., blasting and dredging. Dredging causes the removal of phytoplankton's along with sediment. Primary consumers in the food chain starve to death due to the unavailability of primary producers. The break in the food chain leads to depletion and migration of aquatic fauna, which adversely impact the economy of fishing sector and fisherman community. Revival of the aquatic ecosystem takes a long time once it is depleted.

6. Mitigation of the environmental impacts of underwater blasting

Underwater blasting produces vibration that travels through the water away from the source of Shock waves. Shock waves can cause damage to underwater structures and ecosystem [55]. Intensity of the shock waves depends on Charge per delay, total explosives, number of holes and other blasting parameters. However, the shock wave attenuates with increase in distance from the source of detonation [56]. The rate of attenuation depends on several factors viz. water depth, sediment, sea state, stratification of the water column, temperature, salinity, and other variables [57]. Controlled blasting is used for mitigating the adverse aspects of Underwater blasting. In this technique the controllable parameters of blasting such as Burden, Spacing, Hole Depth, Charge per delay, Total explosive and Type of explosives can be adjusted for curtailing the intensity of shockwaves. The charge per delay is the most significant

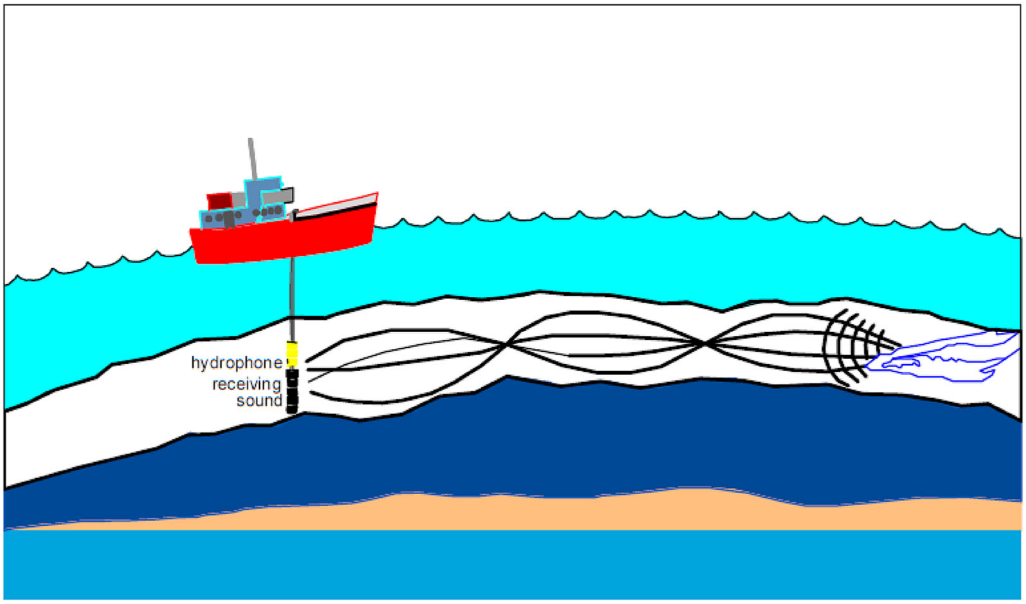

Figure 7. Hydrophone for recording underwater shockwaves [67]

factor in vibration. When multiple blast holes are detonated with the same delay, the generated shockwaves can overlap or converge, resulting in excessive pressure and unwanted effects [58].

Air Bubble curtain and acoustic deterrent devices are generally used in underwater blasting to protect the aquatic ecosystem. Air bubble curtain is considered the most effective tool in reducing the impact of underwater shockwaves and soundwaves [59–62]. Curtain isolates the blasting area by creating an artificial bubble with the help of perforated steel pipes in the sea bed. The pipes are placed at a distance from the blast location to protect aquatic flora and fauna from shock waves as shown in figure 6. Compressed air from the floating pontoons is pumped at a high pressure through the pipes, due to which the air mass bubbles up to the sea surface. When speed of air bubble is 1 litre/metre-minute the shock waves are reduced by 10 times, and when speed of air is doubled, intensity of shock wave is reduced by 70 times [7]. When speed of air is doubled, the discharge rate and number of bubbles increase abruptly and hence the absorption rate of shock waves increases. It protects aquatic species from shock waves by creating a linear screen of bubbles.

Air bubble curtain works on the principle of impedance mismatch [63]. When the sound wave interacts an interface between the water and air, it encounters an impedance mismatch as a result of which the bubble curtain acts as a reflector [64]. In response to the shock waves, bubbles start resonating and absorb significant amount of sound energy. It has been observed that up to 30 dB reduction in sound has been monitored when bubble curtains are deployed with pile driving [65].

Acoustic deterrent devices are also used to minimize the impact of shockwaves on aquatic animals. They emit specific acoustic signals to deter the aquatic animals from coming towards marine construction sites [5]. These devices use random frequency sweeps and tones to alert approaching animals towards blasting location.

7. Instrumentation and monitoring of environmental impacts of underwater blasting

Underwater blasting produces shockwaves that travels through water, away from the source. The shockwaves are measured in terms of pressure and are often referred to as Overpressure. Shockwaves have detrimental impact on the aquatic flora and fauna. To ensure that the shockwaves are within environmental regulation, hydrophone is used. Hydrophone records frequencies from 8 to 500 Hz and can measure pressure changes up to 47 psi [66]. Hydrophone is attached to the seismograph and dropped into the water as shown in figure 7. The hydrophone first measures the ambient underwater pressure and then record any changes in that pressure which occurs after the blast [66].

8. Prediction of induced ground vibration and shockwaves due to underwater blasting

The energy of the explosion is never fully utilized to break the rock mass, much of the energy being wasted as shock and ground vibrations. Accurate prediction of ground vibration and shock wave is important for designing the

Table 1. Recent application of UDB and associated challenges

S. no.	Authors	Excavation site	Highlights of the work	Drawbacks
1.	P Balamadeshwaran *et al.* [6]	Latitude 18° 56.43′ N Longitude 76° 56.24′ E, Maharashtra, India	UDB is employed to deepen the primary harbor channel	· Adverse impact on aquatic life · Blast induced ground vibration
2.	Tripathy *et al.* [27]	Second Liquid Chemical Berth, at Pir Pau for Mumbai Port, Mumbai	UDB is utilized for 25,000 cubic meters of hard rock dredging.	· Blast induced ground vibration
3.	Govoni *et al.* [40]	Pivers Island Channel, North California	Underwater Blasting of bedrock to improve navigation channel	· Shockwaves · Injury and mortality of aquatic organisms
4.	Nielsen *et al.* [45]	Harbor of Sisimiut, west coast, Greenland	Construction of new quay of 120 m length and 10 m deep to serve large vessels	· Shockwaves · Injury and mortality of aquatic organisms
5.	Hempen *et al.* [76]	The Kill Van Kull (KVK) Deepening Project, New York	Rocks are removed using UDB to deepen the KVK strait.	· Shockwaves · Injury and mortality of aquatic organisms

controlled blasting pattern. Researchers around the world have developed relationship between the ground vibration and blast design parameters such as Burden, Spacing, Hole Depth, etc. [8, 68–71]. United State Bureau of Mines (USBM) PPV predictors proposed by Duval and Petkof in 1959 is the most acceptable predictor equation used worldwide shown in Equation (1) [72]. In the recent past, researchers have devised more accurate ground vibration predictors using statistical and machine learning algorithms [73].

$$V = K\left(\frac{R}{\sqrt{Q}}\right)^{-\beta} \quad (1)$$

V = Peak Particle Velocity (mm/s)m R = distance (m) between blast location and instrument position, Q = charge weight per delay (Kg), $R/\sqrt{Q}$ = square-root scaled distance (SSD), K and β = site specific constants

The Ground vibration predictor equation is similar for Surface, Underground or an Underwater blasting. However, in case of Underwater detonation a high intensity shock wave is transmitted to the homogeneous fluid media. This shock wave has two distinct physical characteristics. They are shock wave velocity and local particle velocity. Shock waves can cause damage to the underwater structures such as submerged structures, objects and vessels. Prediction of this shock wave is necessary for deciding the controlled blasting parameters. Cole in 1948 proposed an empirical relationship to estimate the intensity of shock ($\mathbf{P_m}$) wave developed when explosive is detonated Underwater [74]. The proposed relationship is given in Equation (2).

$$\mathbf{P_m} = 52355\left(\frac{R}{Q^{0.33}}\right)^{-1.13} \quad (2)$$

where P_m the pressure in kPa, R is the distance in m and Q is the charge weight per delay in kg. The relationship is valid for the explosives detonated on the surface of the seabed.

Nedwell and Thandavmoorthy [75] estimated the intensity of underwater shock wave in the confined and free explosive detonation. They observed that the shock wave intensity under confined detonation is only 6 % of the free detonation [75].

Similarly, Hempen *et al*. [76] performed the same experiment underwater by detonating four holes at a time. They observed that shock wave of confined shots is 19% to 41% of free detonation pressure [76].

Shock wave depends on several parameters such as maximum charge per delay, depth of water, blast geometry, total explosives fired in a round, etc. Maximum distance (Rmax) up to which shock waves have damaging impact on submerged structures is estimated by the relation given in Equation (3) [77].

$$R_{max} = 1.5Q^{0.333} \quad (3)$$

The distance beyond which there is no impact of blast on the structure is determined by R_{max}. Therefore, for the higher safety of the sensitive structure, a safety factor (SF) is multiplied by the value of R_{max}. The value of SF is adjusted depending on the sensitivity of the structure which is given in Equation (4) [77].

$$R_0 = SF \times R_{max} = SF \times 1.5Q^{0.333} \quad (4)$$

The pressure generated upon detonation of explosives, attenuates with distance from the blast location. This attenuation is known as explosive decay (γ). Since mechanical impedance of water is higher than air hence, attenuation rate in water is slower than air [78]. The peak pressure resulting from underwater blast is p_m. The proposed relationship for p_m is given in Equation (2).

$$\mathbf{p_m} = K_1\left(\frac{M^{1/3}}{R}\right)^{\alpha_1} \quad (5)$$

where K_1 and α_1 are material constants, M is the mass of explosive and R is the radial distance from the point of initiation [73, 79]. Thus, the blast decay constant γ, for the pressure pulse created due to underwater blasting, is given as per Equation (6).

$$\gamma = M^{1/3}K_2\left(\frac{M^{1/3}}{R}\right)^{\alpha_2} \quad (6)$$

where K_2 and α_2 are material constants [79]. Taylor's empirical relation is used to determine the magnitude of pressure at a certain distance from the explosive source, which is given in Equation (7) [80].

$$p(t) = \mathbf{p_m}\exp\left(-\frac{t}{t_0}\right) \quad (7)$$

Where t is time and t_0 is the pulse on the order of milliseconds.

9. Highlights of the actual underwater drilling and blasting

Recent studies on UDB have demonstrated the widespread implementation of this technology at various global sites. The challenges encountered at these sites have already been discussed in various sections of this paper. Specifics of some of these sites are detailed in Table 1.

10. Conclusions

Underwater drilling and blasting offer significant benefits for infrastructure construction, despite the limitations posed by ground vibrations and harmful shockwaves that impact both structures and the aquatic ecosystem. Based on the literature reviews carried out in this manuscript, following outcomes need to be implemented at various underwater blasting sites for the safe and environment friendly rock excavation:

- Quantity and quality of explosive should be selected based on a scientific study to effectively fragment the rock along with reducing the blasting hazards.
- Trial blasts should be carried out to determine the shockwave attenuation rate, which will aid in establishing the shockwave zone within which the absence of aquatic animals can be confirmed.
- Acoustic deterrent devices should be strategically deployed within the shockwave zone to deter fauna from entering the danger zone.

The methods and processes of UDB have various limitations as well, which opens opportunities for future research work in this area. Some of the scopes for future developments have been identified based on the reviews, which are as follows:

- Shockwaves adversely impacts the aquatic life, so it is necessary to develop shock resistant explosives for use in underwater blasting operation.
- Blast waves travel over a longer distance and damage aquatic fauna; development of high-range acoustic deterrent devices will decrease the rate of death per blast.
- Underwater visibility during the course of work is important to enhance the productivity and accountability of excavation.
- After the blast, the sediments remain suspended in the water for a long time, which pollutes the water and adversely affects the benthic and benthos. Therefore, there is a need for the development of dust suppressing chemicals to control sedimentation.
- Researchers have been consistently asserting the need for valid standards for the risk of injury or fatality from underwater blasts. Therefore, there is an urgent need for such standards to protect the underwater ecosystem from underwater blasting.
- All the units mounted on the pontoons are continuously under operation, hence they generate continuous and prolonged vibration, which is transmitted underwater through the pillars/spuds. Moreover, the shock waves generated after the blasting are superimposed with these vibrations and amplify their magnitude. So, it is essential to develop smooth operational machinery that generates lesser vibration during operation.

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