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From Baseline Survey to Management Plan: A Systematic Framework for Port-Specific Mitigation of Underwater Radiated Noise

Amit Kumar Singh[1], G.V.V Pavan Kumar[2,*], P. Sirisha[3] and D.S.P Vidyasagar[4]

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Abstract

The growing recognition of underwater radiated noise (URN) as a significant marine pollutant necessitates the development of actionable management frameworks at the port level, where noise sources are concentrated, and impacts can be particularly acute. While international guidelines exist, a standardized methodology for ports to transition from assessment to implementation is lacking, particularly in regions with high biodiversity and developing maritime infrastructure. This paper presents and demonstrates a systematic, four-phase framework for developing and implementing a Port-Specific Underwater Noise Management Plan (PS-UNMP). The framework was ap- plied in a pilot study at the Visakhapatnam Port Authority (VPA) in India. Phase I involved comprehensive stakeholder mapping and high-risk activity identification. Phase II established a quan- titative acoustic baseline through a strategic hydrophone survey, identifying tugboat operations (peaking at 155 dB re 1 µPa) and construction activities as primary contributors. Phase III focused on data-driven mitigation, revealing that speed reduction from 8 to 3 knots for pilot launches yielded a ~20 dB reduction in URN—a key operational insight. Phase IV integrated these findings into a scalable management plan featuring speed zones, a Noise Monitoring Program (NMP), and stakeholder incentive structures. The study validates the framework as a practical tool for ports to operationalize global guidelines like those from the IMO, bridging the gap between policy and local, effective action for sustainable marine ecosystem management.

Abstract: Index Terms, Underwater Noise Management Plan (UNMP), Port Acoustics, Environmental Management Framework, Stakeholder Engagement, Operational Mitigation, IMO Guidelines, Visakhapatnam Port.

INTRODUCTION

Underwater Radiated Noise (URN) refers to the acoustic energy emitted by marine vessels and offshore structures into the surrounding water column. URN has gained increasing attention due to its implications for marine ecosystem health, naval stealth, offshore construction, and regulatory compliance. Major sources of URN include propeller cavitation, machinery-induced vibrations, hydrodynamic flow noise, and operational activities such as pile driving and towing operations.

Ports are critical nodes of global trade but also hotspots of anthropogenic underwater noise, generated by vessel traffic, cargo handling, and maintenance activities [1]. This noise pollution poses well-documented threats to marine fauna, including communication masking, behavioral disruption, and habitat degradation [2]. In

***Author for Correspondence**
G.V.V Pavan Kumar
E-mail: gvvpavankumar@imu.ac.in

M Faculty, School of Naval Architecture and Ocean Engineering Indian Maritime University Visakhapatnam Campus Visakhapatnam, Andhra Pradesh, India-531035

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response, the International Maritime Organization (IMO) has issued revised guidelines for URN reduction, and initiatives like the GloNoise Partnership aim to foster global collaboration [3] [4]. However, a significant implementation gap persists. Port authorities, especially in emerging economies, often lack a clear, structured pathway to translate these non-mandatory guidelines into effective, site- specific action plans that account for local operational realities, ecological sensitivities, and stakeholder dynamics [5].

This paper addresses this gap by proposing a generalized, sys- tematic framework for developing a Port-Specific Underwater Noise Management Plan (PS-UNMP). Using the major Indian port of Visakhapatnam (VPA) as a case study, we demonstrate the application of this framework from initial scoping and baseline assessment to the formulation of targeted mitigation measures and a continuous improvement plan. The objective is to provide a replicable blueprint that enables ports worldwide to proactively manage their acoustic footprint in a scientifically informed and operationally feasible manner.

LITERATURE REVIEW

Underwater radiated noise (URN) has emerged as a sig- nificant environmental stressor in marine ecosystems, with growing scientific and regulatory attention over the past two decades. Early studies primarily focused on naval and indus- trial applications, but recent research has expanded to ecolog- ical and regulatory domains due to increasing anthropogenic activities in coastal and offshore waters.

Ecological Impacts of URN

Research has consistently demonstrated that elevated URN levels adversely affect marine fauna, particularly cetaceans, fish, and invertebrates. Erbe et al. (2019) documented behav- ioral disruptions in humpback whales exposed to ship noise, including altered vocalization patterns and avoidance behav- iors [6]. Similarly, Williams et al. (2022) reported reduced foraging efficiency in fish species due to masking of acoustic cues in noisy environments [7]. Chronic exposure to high- intensity noise sources such as pile driving and seismic surveys has been linked to physiological stress, hearing loss, and habitat displacement in sensitive species [8].

Major Sources and Characterization

URN originates from multiple anthropogenic activities, with commercial shipping identified as the dominant contributor in many regions. McKenna et al. (2021) quantified source levels from various vessel types, highlighting container ships and tankers as particularly significant emitters due to propeller cav- itation and machinery noise [9]. Non-vessel sources, including dredging, construction, and renewable energy installations, have also been characterized. Van der Graaf et al. (2023) emphasized the intermittent but high-intensity nature of pile- driving noise, which can exceed 180 dB re 1 μPa at source [10].

Monitoring and Measurement Techniques

Advances in acoustic monitoring technology have enabled more precise URN assessments. Merchant et al. (2020) re- viewed autonomous hydrophone systems and their application in long-term soundscape monitoring, noting improvements in spatial coverage and data resolution [11]. Standardized metrics such as sound pressure level (SPL), sound exposure level (SEL), and frequency-weighted indices are now widely adopted for regulatory compliance and impact assessments [12].

Regulatory Framework and Guidelines

The International Maritime Organization (IMO) has been instrumental in developing non-mandatory guidelines for URN reduction, recently revised in 2023 [3]. Regional frameworks, such as the European Union’s Marine Strategy Framework Directive (MSFD) Descriptor 11, mandate member states to achieve Good Environmental Status for underwater noise [13]. However, implementation remains uneven, with Santos et al. (2025) noting a gap between policy formulation and port-level action, especially in developing maritime economies [1].

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Mitigation Strategies and Management Approaches

Mitigation measures span operational, technical, and admin- istrative domains. Speed reduction has been identified as one of the most effective operational measures, with Veirs et al. (2021) reporting a 5 dB to 10 dB reduction per knot decrease in vessel speed [14]. Technical solutions include hull and propeller optimization, bubble curtains, and noise-reducing coatings. Vakili et al. (2025) emphasized the importance of stakeholder engagement and incentive-based mechanisms, such as green port fees, to encourage adoption [5]. Despite these advances, a systematic, port-specific management frame- work remains largely absent from the literature, a gap this paper aims to address.

A FOUR-PHASE FRAMEWORK FOR PORT-SPECIFIC UNMP DEVELOPMENT

The proposed PS-UNMP framework is structured into four sequential, iterative phases Figure 1, designed to be adaptable to ports of varying size and complexity.

Phase I: Scoping & Prioritization

Objective

To define the operational and ecological context and identify priority noise sources and stakeholders.

Activities

1. *Stakeholder Mapping:* Identify and categorize all en- tities involved in or affected by port noise (e.g., port authority, shipping lines, pilotage, tug operators, fishing communities, environmental agencies, research institutions).
2. *Activity Inventory:* Catalogue all noise-generating port activities (e.g., vessel arrivals/departures, cargo transfer, dredging, pile driving).
3. *High-Risk Screening:* Qualitatively rank activities based on known source levels, frequency of occurrence, and proximity to ecologically sensitive areas or seasons.

Phase II: Baseline Acoustic Characterization

Objective

To quantitatively establish the existing underwater soundscape and validate high-risk sources.

Activities

1. *Strategic Survey Design:* Deploy hydrophones at strategic locations (e.g., entrance channel, inner harbor basins, near sensitive habitats) to capture spatial and temporal variability.
2. *Source Attribution Monitoring:* Record acoustic sig- natures during identified high-risk activities, correlating noise metrics (SPL, frequency spectrum) with operational parameters (vessel type, speed, engine RPM).
3. *Ambient Noise Assessment:* Measure background noise levels during periods of minimal activity to establish a baseline.

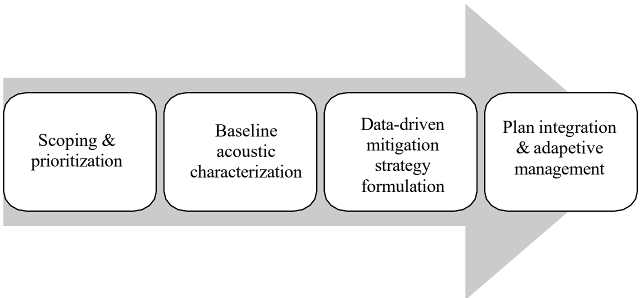

Figure 1. The structure of UNMP development.

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Phase III: Data-Driven Mitigation Strategy Formulation

Objective

To develop targeted, evidence-based mitigation measures.

Activities

1. *Efficacy Analysis:* Analyze monitoring data to identify key acoustic drivers (e.g., speed, machinery type). Test the impact of operational changes (e.g., speed reduction) on recorded URN levels.
2. *Measure Development:* Propose a tiered set of measures.
3. *Operational:* Speed limits, route optimization, schedul- ing of noisy activities.
4. *Technical:* Hull/propeller maintenance protocols, adop- tion of quiet technologies (bubble curtains, low-noise propellers).
5. *Administrative:* Incentive schemes (port fee discounts for quiet ships), stakeholder training programs.

Phase IV: Plan Integration & Adaptive Management

Objective

To develop targeted, evidence-based mitigation measures.

Activities

1. *UNMP Drafting:* Synthesize findings into a formal document outlining goals, measures, roles, and responsibilities.
2. *Monitoring Program (NMP) Design:* Establish a protocol for long-term acoustic monitoring to track progress and compliance.
3. *Stakeholder Implementation Protocol:* Define engagement mechanisms, training schedules, and communication channels.
4. *Adopt a PDCA Cycle:* Institute a Plan-Do-Check-Act framework for periodic review and adaptive improvement of the UNMP.

CASE STUDY APPLICATION: VISAKHAPATNAM PORT AUTHORITY (VPA), INDIA

Phase I at VPA

Stakeholder workshops identified key groups, including VPA operations, pilots, tug operators, and local fishermen. High-risk activities were prioritized as: high-speed movements of port-owned vessels (tugs, pilot launches) and construction- related pile driving, as shown in Figure 2.

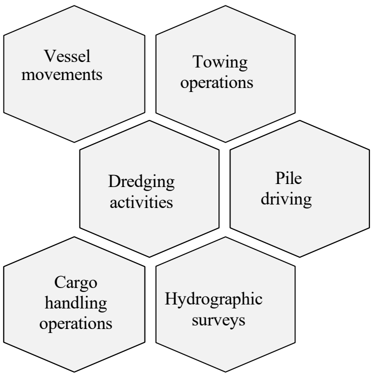

Figure 2. Various port activities leading to Underwater noise within the VPA channel.

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Phase II at VPA

A four-month hydrophone survey provided quantitative val- idation and the underwater sound pressure levels spectrum shown in Figure 3 and ambient levels in Figure 4. Key results included:

(a) *Ambient noise in channels:* 95 dB to 98 dB re 1 µPa.
(b) *Tugboat free-running:* ∼155 dB re 1 µPa at 800 Hz.
(c) *Vibro-pile driving:* >150 dB re 1 µPa in the 3 kHz to 4 kHz band.

Phase III at VPA

Analysis revealed a strong correlation between vessel speed and URN. The most significant finding was that reducing pilot launch speed from 8 to 3 knots decreased URN by approximately 20 dB. This became the cornerstone of the proposed operational mitigation as shown in Figure 5.

Phase IV at VPA

The integrated VPA-UNMP includes:

(i) Mandatory speed zones within the port channel,
(ii) A permanent Noise Monitoring Program with three fixed hydrophone stations,
(iii) An annual incentive review for quiet vessels, and
(iv) Bi-annual stakeholder review meetings under a PDCA cycle.

Figure 3. Underwater noise spectrum for various vessel types operating within the channel.

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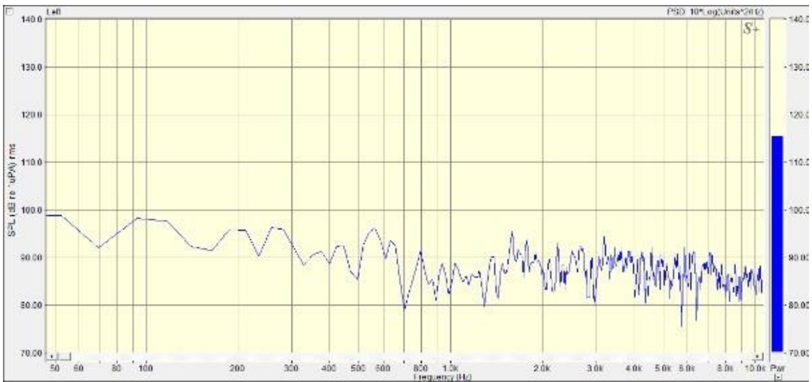

Figure 4. The underwater noise spectrum for ambient levels within the channel.

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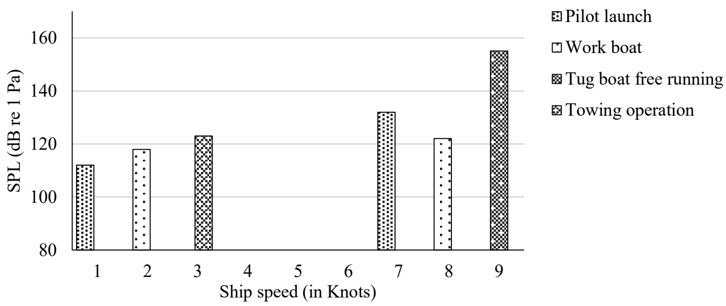

Figure 5. The Sound Pressure Levels during different operations of vessels.

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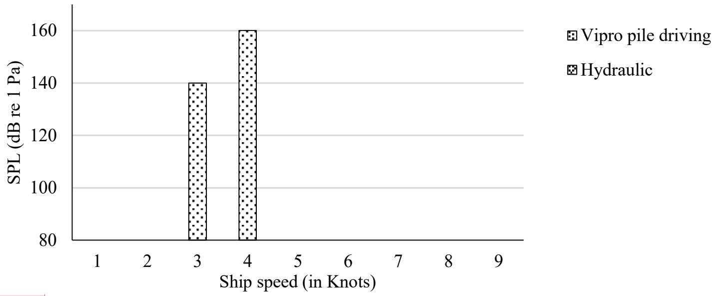

Figure 6. The Sound Pressure Levels for different non-vessel sources.

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In addition to noise generated by vessel movements within the port, several port-related operational activities contribute significantly to URN. These include construction and maintenance operations such as vibro-pile driving and hydraulic pile driving, which are known to produce elevated noise levels over a wide frequency range.

The contribution of these non-vessel sources to the overall underwater acoustic environment of the port is illustrated in Figure 6 component (PDCA cycle) ensures the plan remains relevant amidst changing port operations, traffic patterns, and scientific understanding.

DISCUSSION

The VPA case study demonstrates the framework's utility in moving from generic guidelines to specific, actionable measures. The identification of speed reduction as a highly effective, low-cost intervention underscores the value of local- ized data collection over reliance on generic assumptions. The framework's emphasis on early and continuous stakeholder engagement (Phase I & IV) is critical for ensuring practical feasibility and securing buy-in, which are often the greatest barriers to environmental management plan implementation [15].

The proposed PS-UNMP framework aligns with and op erationalizes higher-level instruments like the IMO's URN guidelines and the EU's Marine Strategy Framework Directive (MSFD) Descriptor 11. Its phased approach allows for incre- mental implementation, which is financially and administra- tively pragmatic for ports. The built-in adaptive management

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Table 1. Measured Underwater Noise Levels at VPA.

Source / Condition	SPL (dB re 1 µPa)	Dominant Frequency
Ambient noise (channel)	*95–98*	*Broadband (10 Hz – 2 kHz)*
Tugboat free-running	155 (peak)	800 Hz
Pilot launch (8 knots)	132	1.2 kHz
Pilot launch (3 knots)	112	800 Hz
Vibro-pile driving	140	3 kHz to 4 kHz
Hydraulic pile driving	160	<500 Hz

RESULTS

The implementation of the four-phase PS-UNMP frame- work at Visakhapatnam Port Authority yielded actionable insights across each phase, culminating in a data-driven management strategy.

Phase I: Prioritized Noise Sources and Stakeholders

Stakeholder mapping and activity screening identified two primary high-risk noise sources:

- Port-owned vessel operations, specifically high-speed movements of tugboats and pilot launches.
- Construction activities, including vibro-pile driving and hydraulic pile driving.

Engagement with 12 stakeholder groups revealed varying levels of awareness regarding URN impacts, with operational staff and local fishing communities expressing the greatest concern.

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Phase II: Acoustic Baseline Characterization

A four-month hydrophone survey provided quantitative baseline data as tabulated in Table 1.

Spatial analysis confirmed that noise levels were highest within the main shipping channel and near construction zones, exceeding 150 dB during peak operations.

Phase III: Mitigation Efficacy

Operational mitigation via speed reduction proved highly effective:

- Reducing pilot launch speed from 8 to 3 knots resulted in a 20 dB reduction in URN as shown in Figure 5.
- Rescheduling pile driving to avoid biologically sensitive periods (e.g., fish spawning season) was identified as a low-cost administrative measure.

Phase IV: Management Plan Components

The finalized VPA-UNMP comprises four actionable com- ponents:

- *Speed zones:* Mandatory 5-knot limit within the inner harbor and 8-knot limit in the approach channel.
- *Noise Monitoring Program (NMP):* Three permanent hydrophone stations for continuous acoustic surveillance.
- *Incentive scheme:* Port fee discounts of 5–10% for vessels meeting IMO noise limits.
- *Adaptive PDCA cycle:* Bi-annual review meetings with stakeholders and annual acoustic reporting.

Validation and Transferability

The framework's applicability was validated through:

- Successful integration of acoustic data into port opera- tional activities.
- Stakeholder acceptance of proposed measures, particu- larly speed reduction.
- Future development of a scalable monitoring protocol adaptable to other major Indian ports.
- The results demonstrate that a systematic, phased approach enables ports to transition from acoustic assessment to imple- mentable noise management, with speed control emerging as a key, low-cost intervention.

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CONCLUSION

Managing underwater noise pollution requires port-specific strategies grounded in local data and stakeholder realities. The four-phase framework presented here—Scoping, Baseline Characterization, Mitigation Formulation, and Plan Integra- tion—provides a systematic methodology for developing such strategies. Its successful application at Visakhapatnam Port has produced a concrete, science-based management plan with speed control at its core. This framework offers a transferable model for ports globally seeking to fulfill their environmental stewardship roles, contribute to international sustainability goals, and proactively address the emerging challenge of anthropogenic ocean noise. Future work should focus on ap- plying this framework in diverse port environments to further refine its components and demonstrate its broad utility.

Acknowledgment

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