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ORIGINAL PAPER

Protecting marine ecosystems from offshore wind noise: a Taiwan cetacean observer enforcement study

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Abstract
Taiwan's offshore wind power plan, launched in 2012, has raised concerns about the impact of underwater noise on marine ecosystems, particularly cetaceans. However, despite the implementation of marine mammal observer systems worldwide, Taiwan's Cetacean Observer system lacks comprehensive regulation, training, and vocational support. To address this gap, a comparative analysis of international marine mammal observer frameworks was conducted, relevant literature was reviewed, and in-depth interviews were conducted with seven stakeholders, including Taiwan's Cetacean Observers, contractors, and marine experts. Four key problem areas were identified through thematic analysis: limited supervision of maritime construction, inadequate training curricula, unstable Taiwan's Cetacean Observer employment and career development paths, and poor integration of cross-department resources. Based on these findings, it is recommended that regulatory supervision be strengthened, establishing a standardized, level-based training and re-certification system, lowering barriers to entry, and developing a one-stop integration platform to improve Taiwan's Cetacean Observer effectiveness and marine conservation outcomes. These practical implications provide a roadmap for optimizing Taiwan's Cetacean Observer system and mitigating impact of underwater noise.

Keywords Acoustic propagation · Baleen whale distribution · Behavioral masking · Bubble screens · Echolocation

Introduction

This study aims to evaluate and optimize Taiwan's Cetacean Observer (TCO) system and explore its legal, regulatory, and operational frameworks, rather than conduct new ecological propagation modeling or physiological biomarker measurements (Jensen et al. 2011; Rolland et al. 2012; El-Dairi et al. 2024). While detailed site-specific acoustic simulations and stress-marker analyses are essential for understanding ecological environments, these methods are beyond the policy-focused analysis of this study.

Since the launch of the first demonstration program in 2012, Taiwan's offshore wind power (OWP) industry has grown rapidly, with plans to exceed 5 GW of installed capacity planned by 2025 and a further 10 GW target by 2035 (Ocean Conservation Administration, Taiwan [OCAT], 2022a). This expansion has led to a dramatic increase in pile-driving operations, generating broadband impulsive sound that can travel for several kilometers in a layered stratified water column (Jensen et al. 2011). The resulting noise field can mask the clicks and social calls of cetacean echolocation, reduce effective communication ranges of some toothed whales by up to 90%, and weaken their foraging efficiency and group cohesion (Erbe et al. 2018).

In addition to behavioral masking, long-term exposure to impulsive and continuous noise has been linked to physiological stress responses in marine mammals and fishes. Rolland et al. (2012) observed a significant decrease in baseline fecal glucocorticoid metabolites in North Atlantic right whales when ambient ship noise was reduced by 6 dB, suggesting that chronic noise elevates stress hormone

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levels. Laboratory experiments in zebrafish revealed changes in endocrine disorder-11-ketotestosterone and estradiol levels after 14 days of continuous noise exposure of 130 dB (He et al. 2025). These physiological impacts can cascade to demographic declines and reduced population resilience (Pirotta et al. 2018).

Numerous international studies (e.g., Martin et al. 2023; Duarte et al. 2021; Hildebrand 2009) have documented how pile-driving noise can lead to permanent hearing impairment, altered migration patterns, and decreased reproductive success in cetaceans. However, despite the growing body of evidence, there is little research that assesses how specific mitigation frameworks, such as marine mammal observer (MMO) systems, are adapted and implemented in Taiwan's unique legal and ecological context. This research gap is particularly salient given the regional specificity of marine mammal habitats and anthropogenic pressures in Taiwan.

In terms of cetacean distribution, there are more cetaceans on the east coast of Taiwan than on the west coast (Fig. 1).

Most of the cetaceans found in the western sea areas of Taiwan are small to medium in size, and rarely investigated. Statistics show that the frequency of cetacean strandings (both live and dead) is high on north, the north-east and Yilan, the shore between Taichung and Miaoli, the shore around Tainan, Kaoshiung, and Pingtung, and the sea areas surrounding Taiwan's outlying islands (OCAT, 2022a, pp. 5–6; Fig. 2). These trends reflect spatial overlaps between cetacean habitats, maritime activity zones, and construction-intensive corridors.

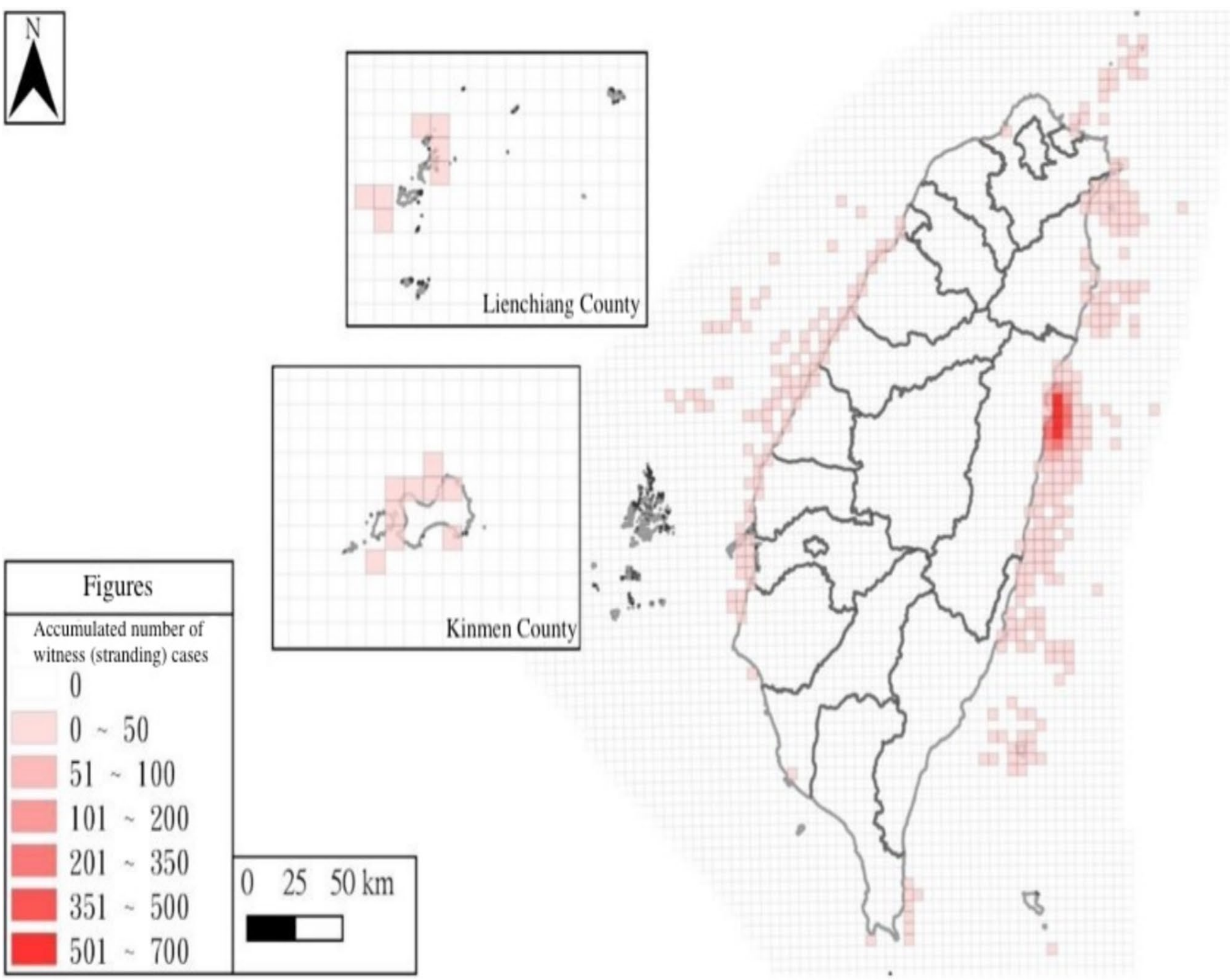

Fig. 1 Location and density plot of cetacean detections in Taiwan waters (5×5 km grids), 1998–2022. *Note*: Data from *Current status of whale and dolphin conservation in Taiwan* (2022b), by Ocean Conservation Administration, Taiwan Marine Conservation Administration. *Source*: Ocean Conservation Administration, Taiwan. (2022b). *Current status of whale and dolphin conservation in Taiwan*. Taiwan Marine Conservation Administration

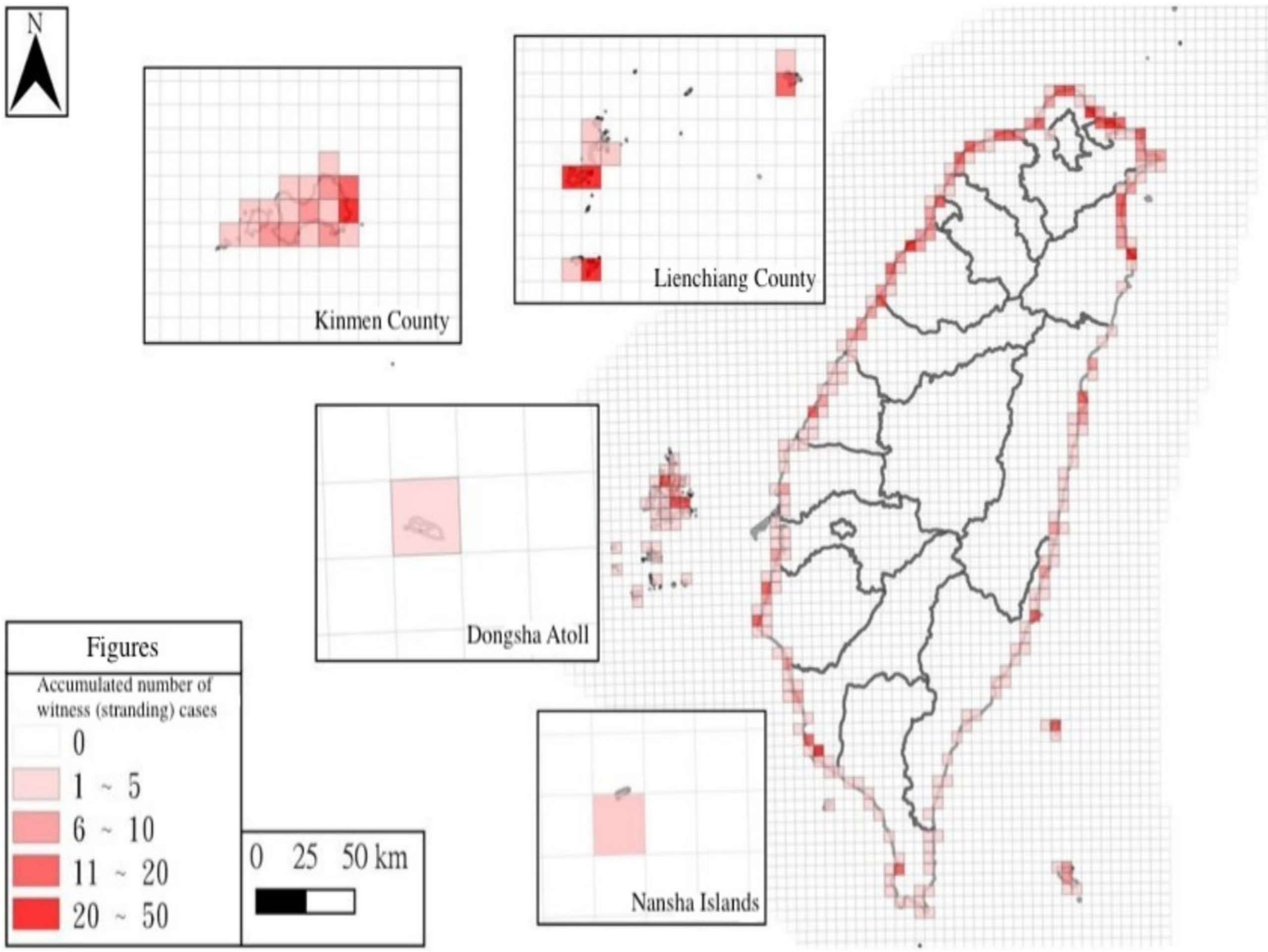

Fig. 2 Frequency distribution of cetacean strandings in Taiwan waters (5×5 km grids), 1994–2022. *Note*: Data from *Current status of whale and dolphin conservation in Taiwan* (2022b), by Ocean Conservation Administration, Taiwan Marine Conservation Administration. *Source*: Ocean Conservation Administration, Taiwan. (2022b). *Current status of whale and dolphin conservation in Taiwan*. Taiwan Marine Conservation Administration

Global marine conservation policies now routinely incorporate MMO and Passive Acoustic Monitoring (PAM) systems into environmental impact assessments of offshore activities (Oros et al. 2024; Louropoulou et al. 2025). Typically, MMO systems contain both trained visual observers and acoustic detectors to monitor cetacean presence. When protected species enter predefined "alert zones," operations must be paused. Such Such schemes, combined with engineering measures such as bubble curtains, can reduce acoustic exposure by up to 25 dB (Bellmann et al. 2020).

Although global MMO research emphasizes standardized training, certification, and enforcement protocols (Duarte et al. 2021; Moretti & Affatati 2023), there has been little academic attention to Taiwan's TCO system. Yang and Wang (2022) highlighted that the length of training and certification standards for TCO differ from best practices in countries such as the UK, US, and New Zealand. Moreover, the existing literature (Ocean Affairs Council 2020; Chen 2019a, 2019b) notes that Taiwan's TCOs often lack enforcement authority, lack adequate institutional support, and face pressure from project developers.

In February 2020, the OCAT issued the "Guidelines for the Cetacean Observer (TCO) system (1st edition), which formalized the cetacean cohort (TCO) system and required developers of offshore wind and other offshore projects to hire certified TCOs and comply with a series of mitigation measures (OCAT 2021). According to the guidelines, developers must integrate the following measures: (1) visually scan surface and subsurface cetacean indicators; (2) real-time acoustic sonar monitoring PAM to detect vocalizations; and (3) the development of shutdown criteria based on predefined acoustic thresholds related to species-specific hearing sensitivities.

Over the past two decades, 32 species of cetaceans have been recorded off the coast of Taiwan, accounting for about one-third of the global diversity of cetaceans, and there is a clear east–west distribution gradient: migratory baleen whales frequently occur in the deeper eastern channels, while coastal odontocetes, such as the Indo-Pacific humpback dolphin (Sousa chinensis), inhabit western straits (OCAT 2022b; Ocean Affairs Council 2020). Stranding hotspots, both live and dead, align with major shipping lanes and construction zones, implicating that anthropogenic noise is a significant stressor for stranding events (OCAT 2022b).

This study builds on international ocean monitoring MMO research and compares it directly to Taiwan's nascent TCO framework, explicitly exploring how global best practices can be adapted to Taiwan's legal, ecological, and administrative contexts. In addition, this study also contributes to theoretical understanding by mapping observer-based mitigation strategies in different jurisdictions and evaluating their applicability to Taiwan's maritime governance regime. This comparative approach takes into account Taiwan's unique bathymetric complexity, species assemblages, and administrative structures, rather than providing generic policy prescriptions.

Global MMO academic research also underscores the importance of standardized, tiered training curricula, rigorous competency assessments, and clear career development paths—elements that contribute to the retention, performance, and legitimacy (Duarte et al. 2021; Moretti & Affatati 2023). However, in Taiwan, TCO training programs lack unified competency benchmarks, re-certification protocols, and independent oversight—gaps that have not been systematically mapped into the underlying legal and administrative frameworks (Yang & Wang 2022).

This comparative approach enables us to situate Taiwan's TCO system within the broader observer-based theoretical framework and make context-specific recommendations based on empirical stakeholder insights and established academic research. By combining rigorous acoustic and ecological science with pragmatic legal design, a TCO that not only meets international standards but also aligns with Taiwan's operational realities and conservation priorities will be developed.

To achieve these goals—while adhering to the scope of our policy analysis—this study employs three complementary methods: Systematic Literature Review: Surveying global MMO frameworks, including acoustic propagation models, insertion loss mitigation assessments, PAM protocols, and ecosystem consequence models (Jensen et al. 2011; Bröker 2019). In-Depth Stakeholder Interviews: Engage with certified TCOs, OCAT and EPA officials, as well as offshore-wind developers, to capture operational insights, compliance barriers, and regulatory bottlenecks. Comparative Legal and Institutional Analysis: Examining UK, US, New Zealand, and EU policies to distill best practices adaptable to Taiwan's legal, cultural, and ecological setting (Oros et al. 2024; Louropoulou et al. 2025).

The primary contributions of this work are threefold: explicitly excluding new ecological models and biomarker assays, thereby defining the scope of the study and thus aligning with research expectations (Jensen et al. 2011; El-Dairi et al. 2024).

Focusing on the nearshore/offshore wind-farm environment in Taiwan and ensure policy relevance through stakeholder interviews and cross-jurisdictional comparisons. Targeted institutional reforms plans are proposed, including enhanced TCO enforcement authority, integrated cross-departmental noise monitoring platforms, and a standardized, tiered training courses aimed at enhancing the effectiveness of offshore wind noise monitoring and cetacean conservation (Moretti & Affatati 2023; Funk et al. 2024a, b).

By bridging rigorous acoustic science with legal and administrative design, Taiwan's commitment to Sustainable Development Goal 14 is supported ("conserve and sustainably use the oceans, seas and marine resources") and professionalize the role of TCO in the rapidly growing offshore wind sector. The study was conducted from January to December 2023 in Taiwan's nearshore and offshore waters.

Materials and methods

Materials

Development of marine mammal observer system

Studies on underwater noise, marine animal auditory range (Fig. 3), and the effect of underwater noise on marine mammals (Fig. 4) have shown that underwater noise can lead to auditory damage and behavioral change in marine mammals using echolocation, and may also have an auditory masking effect.

Richardson et al (2013), Moretti and Affatati (2023), and El-Dairi et al. (2024) pointed to various effects of underwater noise on marine animals, including hearing loss (which may be temporary or permanent), behavioral changes, masking effects, and audibility (chronic stress). Gedamke et al. (2016) indicated that the scale and type of human activities at sea are increasing. Duarte et al. (2021) considered that that cargo, cruise and private yachts increased maritime noise by a factor of 32 during various human maritime activities. In recent years, offshore construction has become a new source of underwater noise, and high-intensity impulse noise from pile driving (e.g., offshore wind power generators, oil platforms, and electrical substations), underwater demolition, and seismic exploration has recorded the greatest impact. Jones (2019) noted that "underwater sound from anthropogenic sources can be so loud that it disrupts marine animals' communications — and can even cause injuries and deaths" (p. 161; see Fig. 5). Duarte et al. (2021) evaluated

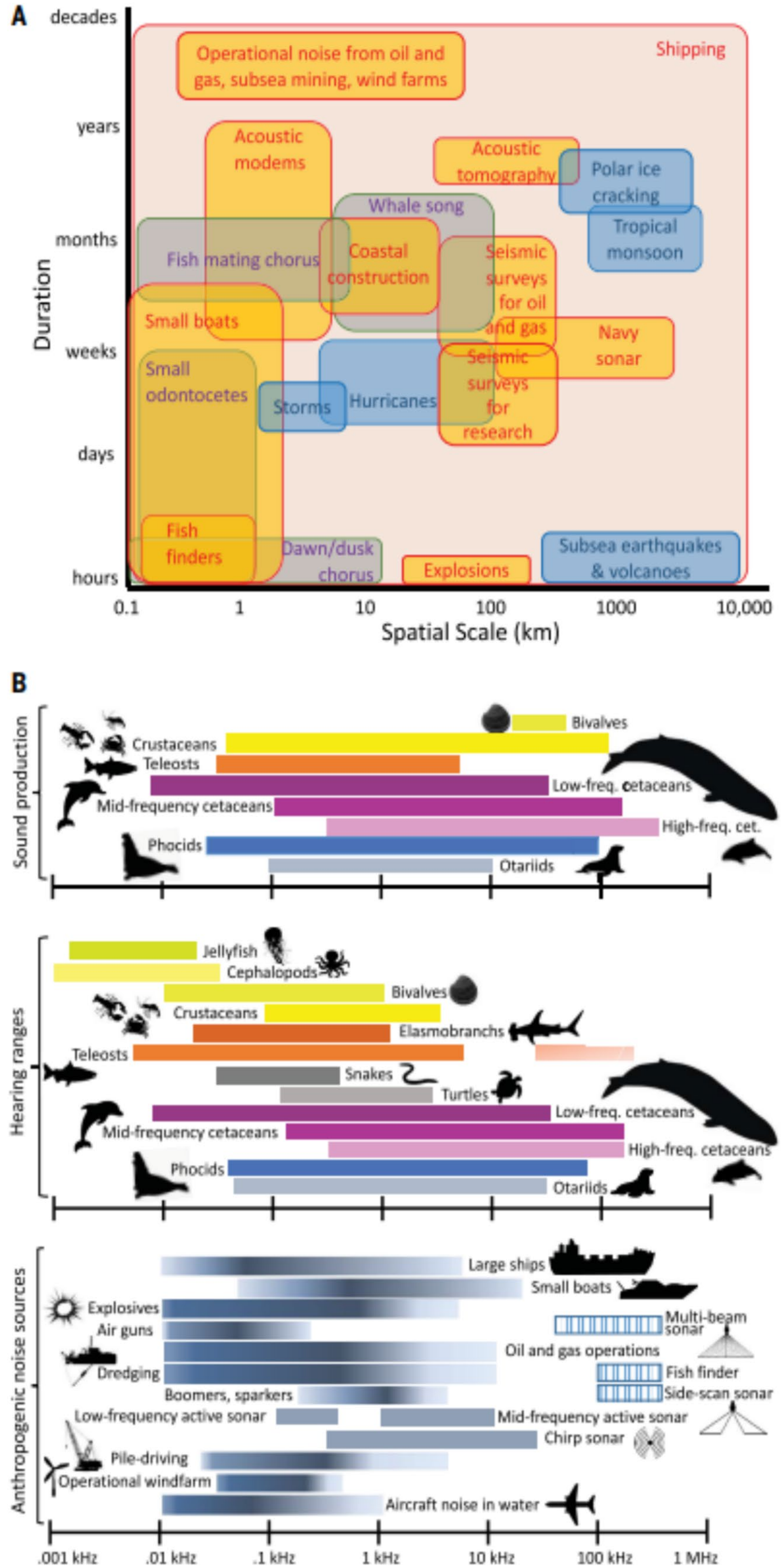

Fig. 3 Sources and animal receivers of sound in the ocean soundscape. *Note*. **A** Stommel diagram showing the spatial extent and duration of selected biophony (gray squares), geophony (blue squares), and anthrophony (yellow squares). Rounded squares indicate the spatial and temporal extent of signals or bouts of signals. Although some sources—such as those used in hydrographic surveys—propagate over limited distances, survey efforts can span large areas (e.g., an entire Exclusive Economic Zone). "Dawn/dusk chorus" denotes the collective daily sounds produced by species such as fish and snapping shrimp. Shipping noise covers a broad range of spatial and temporal scales. **B** Approximate sound-production and hearing ranges of marine taxa alongside frequency ranges of selected anthropogenic sources. These ranges represent each source's dominant frequency band, and the color shading corresponds roughly to its dominant energy band. Dashed lines denote sonar signals, illustrating their multifrequency nature. Data sources are references 9, 18, 25, 53, 75, 83, and 131–139. *Source*: Duarte, C. M., Chapuis, L., Collin, S. P., Costa, D. P., Devassy, R. P., Eguíluz, V. M., … Juanes, F. (2021). The soundscape of the Anthropocene ocean. *Science, 371*(6529), eaba4658

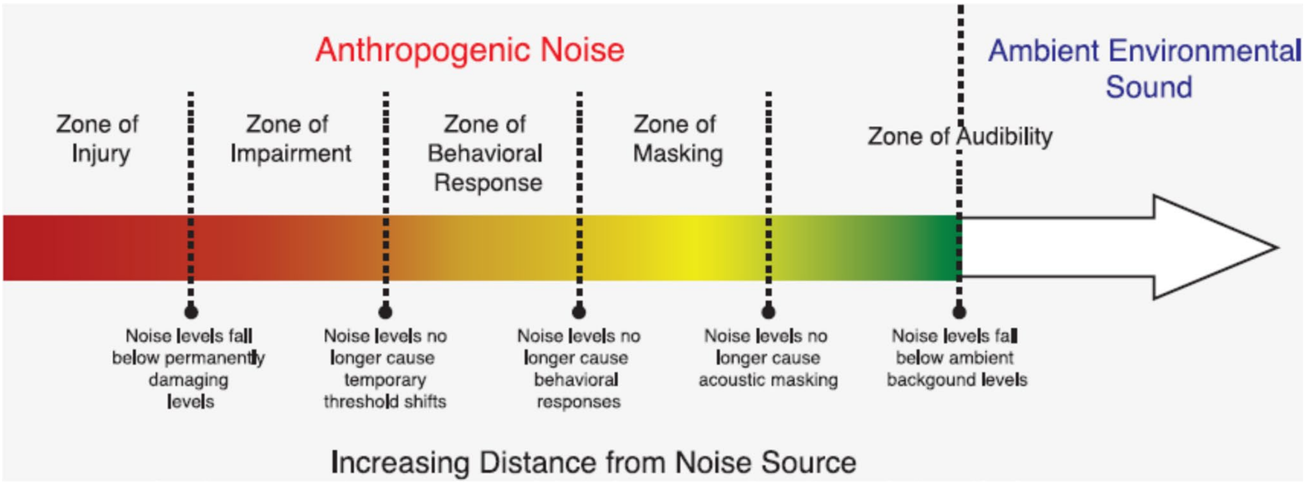

Fig. 4 Conceptual framework illustrating potential noise impacts on marine mammals across auditory-impact zones relative to distance from the sound source. *Source* U.S. Offshore Wind Synthesis of Environmental Effects Research (SEER). (2022). *Underwater noise effects on marine life associated with offshore wind farms* [Report by National Renewable Energy Laboratory & Pacific Northwest National Laboratory for the U.S. Department of Energy, Wind Energy Technologies Office]. Retrieved from https://tethys.pnnl.gov/seer

the impact of underwater noise on marine animals and found that human-generated underwater noise has a huge negative effect on marine animals. These effects include behavioral changes (changes in producing sounds or food ingestion, avoidance, and fear), physical changes (changes in the hearing threshold, physical conditions, and pressure injury), physical responses, physiological changes, death, and other chronic effects (population size, larval development) (Baumgartner et al. 2024). Abramic et al. (2022), Guan and Brookens (2023), and Liu et al. (2023) showed some of the potential impacts of OWP construction on maritime environments. Weilgart (2007) and Hildebrand (2009) pointed out that high-intensity noise generated momentarily or for a short period of time during piling can severely affect marine ecosystems, especially marine mammals that rely on echolocation (Huang, et al. 2023; Southall, et al. 2023).

The development of the MMO system was inspired by studies on the possible negative or destructive effects of underwater noise on marine animals. Many mitigation measures have been developed to compensate for various kinds of human exploitation of the seas. MMO is now the major mitigation measure for pile driving, underwater demolition, seismic exploration, and other large-scale maritime constructions. Countries including the UK, Ireland, the USA, Canada, New Zealand, and Australia, have made laws and developed monitoring guidelines for MMO and set up organizations for related matters. Therefore, in 2020, Taiwan established its CO system and amended the TCO system operation guideline in the same year.

As marine development and construction continue to deepen, people are increasingly aware of the importance of protecting marine ecosystem. Many countries and research institutions have proposed new monitoring guidelines or revised versions to ensure the effectiveness of the monitoring guidelines (Department of Fisheries and Oceans Canada [DFO] 2020; Environmental Defenders Office [EDO] 2019). The CO system was implemented in Taiwan in 2020. However, the CO system and many related areas need to be improved, especially in terms of the supervision and administration of developers and the training system, certification, supervisory power, career development, and employee benefits of COs (OCAT 2021).

Review of the Taiwan cetacean observer system

The Government authorities should conduct pre-construction review, construction supervision and completion tracking for each construction project. For this purpose, MMOs and COs are commonly used as mitigation measures and play a supervisory role in maritime construction that produces high-intensity underwater noise. This study reviewed the approach adopted by many countries including France, the UK, Ireland, the US, Canada, New Zealand, and Australia and found that these governments have amended their laws and monitoring guidelines and adopted MMO as a mitigation measure to reduce the negative impacts of underwater noise from maritime construction (such as pile driving) on specific marine species. Observers visually perform real-time monitoring to prevent protected species from entering a high-impact noise zone (or the alert zone). In 2020, OCAT learned from the UK, established the TCO system, and published the TCO system operation guideline. For OWC pile driving, it is explicitly stated in the guideline that COs are required. For other maritime constructions, whether a CO is

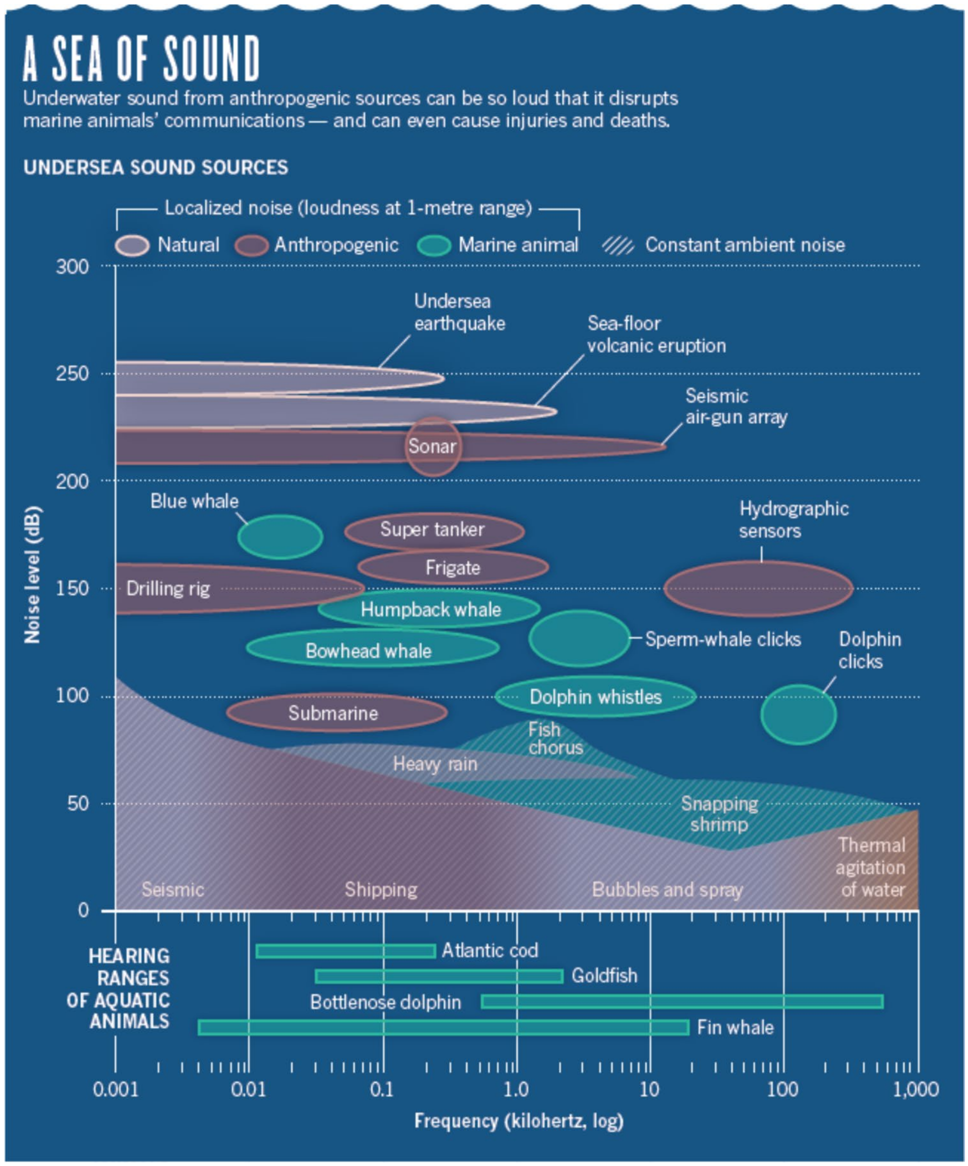

Fig. 5 A sea of sound. *Note*: Underwater sound from anthropogenic sources can be so loud that it disrupts marine animals' communications and can even cause injuries and deaths. *Source*: Jones, N. (2019). The quest for quieter seas. *Nature, 568*(7751), 161

required depends on the results of the environmental impact assessment. The TCO system has been implemented for four years, and to improve and update the TCO System Operation Guideline (third edition, issued in June, 2021), suggestions and comments were collected from various parties. The CO training system, CO qualification, the operating procedure for developers and related forms have also been optimized (OCAT 2021). Although OCAT has been working on enhancing the CO system, the CO system still requires further enhancement compared with those in more developed countries. The primary shortcomings are as follows: 1) OCAT can legally require the developer to submit the CO monitoring plan and the original records and reports for auditing and tracking, and can appoint COs monitoring experts to oversee them. However, depending on the construction and the environment, the mitigation measures are still determined by the developer in accordance with the environmental impact assessment commitment made in its environmental impact assessment report (according to Articles 6 and 11 of the Environmental Impact Assessment Act) and the environmental impact assessment review conclusion. In other words, the mitigation measures are not determined by the government authority, i.e., OCAT (OCAT 2019).

The TCO system framework was established based on Taiwan's Wildlife Conservation Act, Environmental Impact Assessment Act, and the TCO System Operation Guideline (Fig. 6). This study examined the current TCO system framework, the MMO systems in other countries, and related studies, and finds that the main problems include: (1) limited government supervisory power, (2) COs are employed by the developer itself or represented by an agency entrusted by the developer. Similar to maritime monitoring in the UK; both

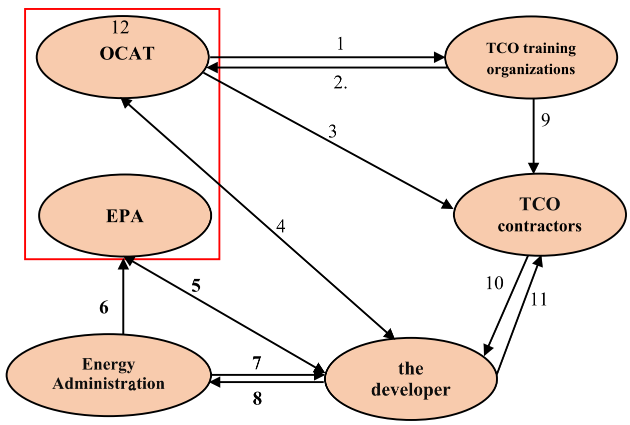

Fig. 6 Taiwan cetacean observer system framework. *Note*: The framework comprises: (1) lecturing permits, supervision, and tracking; (2) application for and submission of training reports; (3) recognition of TCO and equivalent qualifications, plus TCO assignment and administration; (4) submission of CO supervision plans, original records, and reports, and establishment of standard pile-driving procedures; (5) inspection findings and ongoing supervision; (6) forwarding of environmental impact assessment reports; (7) consolidated assessment results for development-permit issuance; (8) development applications, including submission and evaluation of assessment reports; (9) provision of TCOs who have completed training; (10) commissioning; (11) provision of TCOs or observers with equivalent qualifications; and (12) joint supervision of developers by related agencies, with the Environmental Protection Administration overseeing CO monitoring plans and reports. Items 5–8 (in bold) are not regulated by this system; they illustrate interagency relationships and administrative authority

MMOs and COs are employed by the developer or developers' contractors, and the most common disadvantage is that the observer is "advised" not to record their cetacean observation, otherwise construction may be slowed down (Chen 2019a). (3) The procedure for submitting the monitoring report or record varies among countries. (4) The applicable regions, control items and protected species listed in the national monitoring guidelines vary. The current TCO systems are only for cetaceans, but according to studies worldwide, underwater noise may have a negative impact on other types of marine animals, such as sharks and sea turtles.

There are seven types of sea turtles in the world, and five which are protected and can be found in the waters of Taiwan (Ocean Affairs Council 2023). (5) The approach of law enforcement differs among countries. For the minimum manpower requirement, each observation vessel should be equipped with at least two TCOs. In terms of shifts, the TCOs should change their observation sites at least once an hour and take at least 20 min of rest every four hours. For working hours, according to Taiwan's Labor Standards Act, even if the COs agrees to extend the working hours, the daily working hours shall not exceed **12 h**. Nevertheless, these principles are not explicitly stated in the TCO System Operation Guidelines. Monitoring guidelines in the UK, the US and New Zealand all state that that the maximum working time in a 24-h period must not exceed 12 h. Although each country has relevant regulations, monitoring guidelines and the status of marine ecosystems vary, so it is questionable whether persons with equivalent observer qualifications in other countries are familiar with Taiwan's laws and regulations, monitoring guidelines, and environmental impact assessment commitments. Lastly, when a CO is performing a mission at sea, the developer should ensure that the observer completes safety-related training prior to performing a mission at sea, depending on the vessel, type or location of construction, safety regulations and legal requirements. Order of construction suspension: The TCO does not have the authority to order the developer to stop the construction; only to make recommendations. Similar to the regime in the UK and Ireland, the developer is required to comply with the environmental impact assessment (Chen 2019b), but in the US, Canada, New Zealand, and Australia, the monitors have the power to stop the construction. With regard to the training system, the main issues are as follows: (1) The trainees might be subordinates of the training agency. According to the TCO System Operation Guidelines, companies are organizations that can set up a training agency, so that the developer can commission a CO contractor to train its subordinates, and after the training is completed, these subordinates can monitor the developer. (2) The training curriculum and hours vary from country to country. The TCO system guidelines clearly specify the training sessions and times for the CO. (3) The experience-based classification system vary from country to country. Currently, there is no empirically based classification system, but it is used in the UK, Ireland, and New Zealand. (4) Different countries have different definitions of training completion. With the exception of New Zealand, which prescribes the level required at the end of the training, most countries (including Taiwan) only specify the required competencies but do not set standards. (5) The CO training certificate of completion is not globally recognized and is only valid in Taiwan. In summary, in order to effectively reduce the impact of the underwater noise produced by OWP construction on cetaceans in Taiwan, the Taiwan Marine Environmental Protection Association has formulated a TCO system and TCO system operating points based on **Article 12** of the Wildlife Conservation Act and **Article 18** of the Environmental Impact Assessment Act. However, compared to other national systems, the TCO system still has the above shortcomings.

Acoustic propagation and species-specific impact assessment

Theory and methods Modeling of sound propagation in the marine environment often uses multi-layer sound-speed profiles and ray-tracing or normal-mode algorithms to simulate how construction or vessel noise travels under different hydrological conditions (Jensen et al. 2011). Such models compute received sound levels at different ranges and depths by taking into account refraction, absorption, and seabed interactions. Species-specific impact assessments then combine these propagation maps with marine mammal distribution and hearing sensitivity data to delineate “risk zones” where noise exceeds biologically relevant thresholds (Hildebrand 2009; Rolland et al. 2012). Physiological monitoring, such as measuring stress-related biomarkers in feces or blood, can provide direct evidence of the impact of noise at the individual level (El-Dairi et al. 2024).

Representative research findings Jensen et al. (2011) developed a computational ocean-acoustic models to simulate underwater noise from pile driving and vessel traffic by tracing acoustic beams through stratified water layers, demonstrating how temperature and salinity gradients alter propagation paths and focal zones (Jensen et al. 2011). Hildebrand (2009) reviewed global sources of ambient noise and showed how noise maps can be combined with species distribution data to identify high-exposure “hotspots” for cetaceans, leading to targeted mitigation (Hildebrand 2009). Erbe et al. (2018) synthesized evidence from the behavioral and acoustic masking responses of dolphins and whales exposed to ship noise, highlighting the reduction of communication ranges and changes in calling frequency (Erbe et al. 2018). Rolland et al. (2012) provided the first physiological link, showing that a 6 dB reduction in ship traffic noise in the Bay of Fundy was associated with a significant decrease in stress-hormone metabolites in North Atlantic right whales, implying that chronic noise increased baseline stress (Rolland et al. 2012).

Research gaps Despite the existence of global models, there is a paucity of site-specific propagation studies in Taiwanese waters that integrate locally measured sound-speed profiles with regional marine mammal sighting data. The Species-level hearing thresholds for many coastal odontocetes in this region are still not well characterized, which limits the accuracy of risk-zone delineations. Moreover, few studies have coupled acoustic exposure simulations with physiological or molecular biomarkers to validate predicted impacts in local populations (El-Dairi et al. 2024). To inform national policy, future work should develop high-resolution propagation models tuned to Taiwan’s complex bathymetry, and use passive acoustic monitoring and non-invasive stress analysis for field validation.

Noise mitigation effectiveness and cumulative noise impacts

Theory and methods Underwater noise mitigation is typically evaluated using physics-based propagation models that simulate insertion loss (i.e., the reduction in received sound levels after mitigation measures) at critical frequencies (**100–1 000 Hz**) and ranges (**≤ 1 km**). These models divide energy into structure-borne, seismic, and airborne pathways to quantify the attenuation effect of bubble-screen curtains, compliant pile sleeves, and dewatered cofferdams attenuate sound (Cefas 2015; Bellmann et al. 2020). To assess cumulative impacts, simulated exposure levels are combined with non-invasive physiological and molecular biomarkers: fecal glucocorticoid metabolites were indicative of chronic stress in marine mammals (Rolland et al. 2012), while gene-expression profiles of oxidative-stress and immune markers reveal sublethal effects after prolonged noise exposure (El-Dairi et al. 2024). Recent extensions have applied these biomarkers to commercially important fishes—monitoring oxygen consumption rates, osmolality, and catecholamine responses under noise from pile-driving and turbine-operation noise (Kim et al. 2025).

Representative findings Insertion-loss performance: Bubble curtains reduce impulsive pile-driving noise by **10–25 dB**; full cofferdams achieve ~ **20 dB** broadband reduction; compliant coatings (**2–8 in**) yield ~ 10 dB attenuation (Stokes et al. 2010). German trials of Noise Mitigation Screens and Hydro-Sound Dampers report 8–15 dB losses, with confined bubble rings up to **25 dB** under optimal conditions (Lamoni 2023). Cost-effective engineering solutions—such as inflatable piling sleeves (**€20 000/pile**) and foam-filled tubes (**€25 000/pile**)—project 15–20 dB reductions with minimal workflow disruption (Nehls et al. 2007; Lucke & Siemensma 2013).

Physiological stress in mammals: **A 6 dB** decrease in ship-noise levels in the Bay of Fundy corresponded to significantly lower fecal glucocorticoid metabolites for right whales in North Atlantic, confirming chronic noise as a stressor (Rolland et al. 2012).

Fish metabolic responses: The oxygen consumption rate (**0.316 vs. 0.225 mg** $\mathbf{O_2 \cdot g-^{1} \cdot h^{-1}}$**,** $p<0.01$) and osmolality (**271 vs. 224 mOsm**$\mathbf{\cdot kg^{-1}}$**,** $p<0.055$) were significantly increased in juvenile large yellow croaker exposed to 24-h piling noise, whereas the metabolism of flounder was decreased under the same conditions—highlighting species and diel-specific sensitivities; The variation caused by the noise of turbine operation is negligible (Kim et al. 2025).

Endocrine disruption in fish: Fourteen-day exposure to **130 dB** continuous noise (**100–1 000 Hz**) in zebrafish depressed courtship behavior, reduced spawning, and altered sex-steroid levels via hypothalamic-pituitary–gonadal axis gene-expression changes, illustrating chronic noise as an endocrine disruptor (He et al. 2025).

Research gaps Site-specific modeling: Taiwan’s complex bathymetry and seasonal sound-speed variations have not been fully incorporated into high-resolution insertion-loss simulations.

Species-specific thresholds: Audiograms of key odontocetes and commercial fish in Taiwanese waters remain incomplete, limiting accurate delineation of biologically relevant risk zones.

Local field validation: In situ trials of mitigation systems (e.g., bubble curtains) are rare under tidal conditions and seabed conditions in Taiwan.

Long-term biomonitoring: Multi-seasonal physiological and molecular studies are needed to track population recovery trajectories after mitigation implementation.

Regulatory alignment: National guidelines have not yet to adopt standardized, risk-based frameworks (such as those in the EU Marine Strategy Framework Directive) that link continuous noise thresholds to habitat loss and population-level impacts.

Real-time passive acoustic monitoring and shut-down systems

Theory and methods Real-time PAM systems employ an array of hydrophone—fixed (moorings, platforms), towed, or vehicle-borne—to continuously capture underwater sound and stream it to ashore or vessels via cables, satellite, or cellular links. On-board preprocessing (e.g., band-limited filtering, compression) minimizes bandwidth and latency (Macrander et al. 2021; Thode et al. 2021). Automated detectors, such as the spectrogram edge-detector and matched-filter routines in PAMGuard (Passive Acoustic Monitoring Guardianship), can identify cetacean vocalizations (whistles, clicks, upcalls) within seconds (Gillespie et al. 2013). When preset predefined detection thresholds (number of calls, received level) are reached, the decision logic triggers immediate cessation ("shutdown") of noise-generating activities (pile driving, seismic surveys, turbine operation). Recent advances include the use of machine-learning classifiers (e.g., CNNs, random forests) to train under different noise conditions to reduce false positives and enhance species discrimination (Niu et al. 2023).

Representative findings Detection performance: Field trials in Germany and the U.S. have reported that PAMGUARD had a delay of less than 5 s for dolphin whistles and right-whale upcalls at detection distances of up to 2 km, and successfully initiated the shutdown procedure (Gillespie et al. 2013).

Operational efficiency: A decade-long study of oil and gas platforms in North and Irish Sea demonstrated that integrating real-time PAM with visual observers can cut crew working time in half while maintaining detection rates (Todd et al. 2015).

Collision avoidance: In the Bay of Fundy, buoy-based PAM combined with ship alert systems, reduced North Atlantic right-whale ship strikes by than 30% by enforcing shutdown ships after an upward signal was detected (Soldevilla et al. 2014).

Adaptive feedback: German offshore-wind projects used live acoustic feedback to regulate pile-driving energy, preventing mitigation thresholds from being exceeded, and reduce installation time by 20% (Verfuss et al. 2016).

Research gaps Ambient noise masking: High broadband noise (**> 110 dB re 1 μPa**) from waves, wind, and concurrent operations can reduce the sensitivity of the detector, especially for high-frequency calls. There is a need for systematic evaluation of performance under different sea states (Yang et al. 2020a, b).

Localization challenges: Multipath and varying sound-speed profiles in shallow or tidal waters can affect array-based localization, reducing effective exclusion radii. Enhanced ray-tracing and adaptive beamforming algorithms are required (Mellinger et al. 2007).

Latency reduction: The current detection of a shutdown delays (about 8–12 s) may be insufficient for fast-moving odontocetes. Low-latency pipelines and edge-computing architectures should aim for an end-to-end response of less than 5 s (Faulkner et al. 2018).

Threshold standardization: Detection criteria (number of calls, received level) vary among projects. The establishment of a framework based on biological information and risk (similar to the EU Marine Strategy Framework Directive) would help improve consistency and regulatory acceptance (Faulkner et al. 2018).

Mobile integration: Fixed arrays have imperfect synchronization protocols with autonomous underwater vehicles or gliders, limiting spatial coverage and reaction speeds.

Ecosystem-level long-term effects

Theory and methods Ecosystem-level impacts of chronic underwater noise are typically evaluated by linking individual disturbance to population and community outcomes. Population Consequence of Acoustic Disturbance (PCAD) models translate behavioral and physiological responses into demographic rates (survival, reproduction) over time (Pirotta 2022). Community- and food-web models then embed species-specific noise sensitivities (e.g., masking, displacement) into trophic interactions, projecting shifts in community composition, energy flow, and nutrient cycling under sustained noise regimes (Fanelli et al. 2022).Long-term field programs—combined with fixed passive acoustic recorders, visual surveys, and biomarker sampling (e.g., fecal glucocorticoids, gene-expression assays)—are used to validate these model predictions by tracking multi-year trends in abundance, diversity, and physiological stress (Merchant et al. 2022).

Representative findings Mediterranean community shifts: Chronic shipping, pile driving, and seismic noise disrupt communication and foraging for fish and invertebrates, leading to trophic cascades (e.g., algal overgrowth following sea-urchin displacement) that restructure the habitat of benthic organisms (Fanelli et al. 2022).

Global pollutant synthesis: Bibliometric and regional case studies confirm that even sub- damaging noise exposure can reduce population growth rates and alter community assemblages across taxa and habitats over decades (Williams et al. 2015).

Behavior to survival linkage: European eels exposed to harbor noise had a 50% reduction in startle responses to predators and higher metabolic stress, implying their survival and recruitment rates decreased at the population level (Simpson et al. 2015).

Integrate the EU Marine Strategy Framework Directive (MSFD): A decade of monitoring under the MSFD has demonstrated that combined impulsive and continuous noise data can support ecosystem-scale state assessments; however, quantitative thresholds for Good Environmental Status remain undefined for most species due to insufficient population-level data (Merchant et al. 2022).

Research gaps Local demographic data: The survival and fecundity of Taiwanese marine organisms at specific ages and stages in chronic noise environments are unknown, which limits the accuracy of the PCAD model.

Multi-species trophic models: Few studies have integrated noise sensitivities across multiple species and trophic levels to predict cascading ecosystem effects in nearshore habitats (Hubert 2021).

Longitudinal monitoring: The lack of **a 10-year time series of noise exposure**, community indicators, and biomarker indicators in Taiwan hindered the field validation of model predictions (Southall et al. 2021).

Policy-relevant thresholds: Outside the EU, risk-based frameworks linking continuous noise levels to ecosystem service indicators or community-level risks have not been developed, hindering regulatory application (Borsani et al. 2023).

Synergistic stressors: The role of the interaction between noise and other pressures (chemical pollution, climate change) in driving long-term ecosystem change remains unclear (Cabral et al. 2019).

Together, these foundational studies provide a scientific basis for our subsequent policy recommendations. Going forward, collaboration with marine ecologists will be essential to translate model-derived risk zones into practical observer operating guidelines.

Methods

Research design and participant selection

The goal of this study was to understand the roles and interactions of public and private organizations involved in Taiwan's TCO system and to identify areas for improvement. Accordingly, four stakeholder groups were investigated: (1) COs, their contractors, and training agencies; (2) government agencies; (3) environmental protection groups; and (4) developers. The study framework is presented in Fig. 7.

To ensure that participants possessed relevant expertise and represented diverse perspectives, this study employed a purposive sampling strategy. Specifically, the inclusion criteria were established as follows: (a) At least two years of experience working as a CO and direct monitoring involvement at three or more OWP pile-driving sites; and (b) representation from each stakeholder category—government officials responsible for TCO oversight, contractor project managers overseeing OWP construction, environmental NGO representatives advocating for marine conservation, and academic or policy experts specializing in marine ecosystems. These criteria ensured that interviewees had first-hand knowledge of TCO operations and could speak authoritatively about system strengths and weaknesses (Guest et al. 2006; Patton 2002).

The recruitment process is as follows: Reach out to known TCO practitioners and ask them to refer more participants (snowball technique) until seven potential interviewees are identified. All interviews are conducted in a face-to-face to facilitate rapport and gather richer data information. Since participant saturation was observed in the seventh interview—no new themes or codes emerged—no other participants were recruited (Guest et al. 2006; Naeem et al. 2024). The final sample included four COs, one contractor, one marine conservationist, and one marine policy expert.

A semi-structured interview protocol guided each session. Questions explored current TCO practices; training experiences; perceptions of legal, regulatory, and administrative support; challenges in marine construction supervision; and suggestions for system enhancement. The interview guidelines have been piloted with two additional COs not included in the final sample to improve question wording and ensure clarity.

Data collection procedures and time frame

Data collection lasted for six months, from January to June 2023. All interviews were conducted at locations convenient to participants, such as TCO training centers, government offices, or mutually agreed meeting rooms. Each interview lasted 60 to 90 min and was audio-recorded with participant consent. Participants were informed of the purpose of the

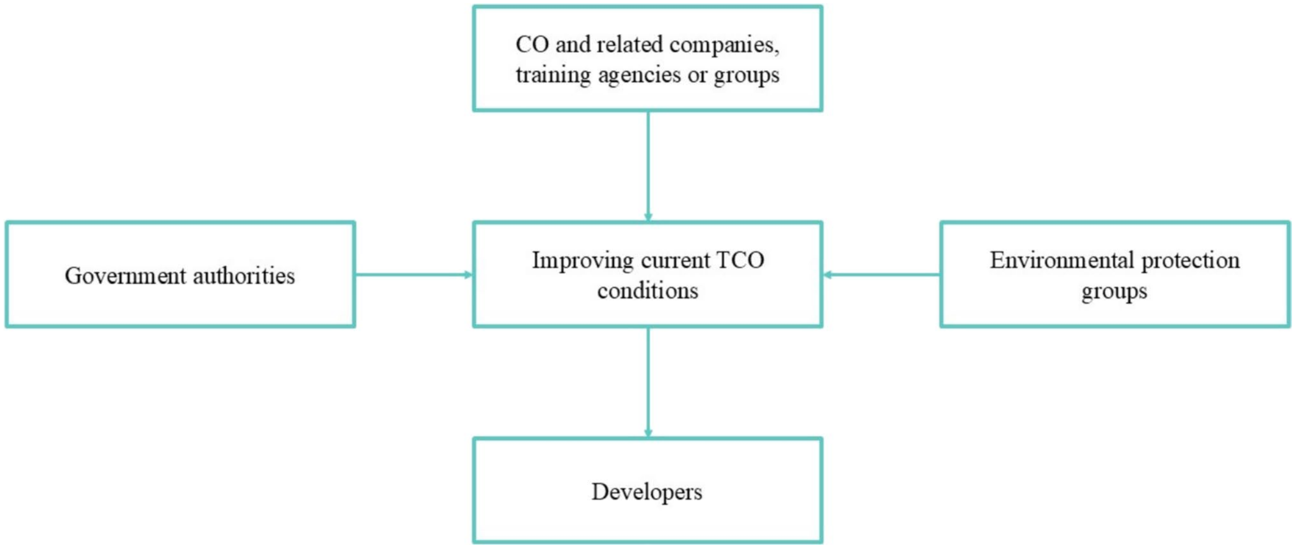

Fig. 7 Research framework

study, confidentiality agreement, and their right to withdraw at any time.

The targeted period for contextual analysis extended from 2012 (when Taiwan announced its OWP plan) to 2023 (the final data collection date), reflecting the developmental trajectory of OWP infrastructure and the TCO system. This temporal scope allowed for a comprehensive examination of policy evolution, iterations of training guideline (e.g., OCAT 2021 updates), and operational trends in marine mammal observations.

Data processing and qualitative reliability measures

Immediately following each interview, the primary researcher produced a verbatim transcript in Chinese. To enhance transcription accuracy, the researcher compared the audio recording with the transcript and contacted participants if clarification or missing information was identified. Each transcript was anonymized and labeled with a code (A–G) and the participant's affiliation.

To address potential researcher bias and improve trustworthiness, several strategies were implemented:

Reflexivity journal Prior to conducting interviews, the primary researcher maintained a reflexivity journal in which they recorded personal assumptions, emotional reactions, and preconceptions about the TCO system (Lincoln & Guba 1988). Entries were updated after each interview to highlight emerging biases and to reflect on how these might influence question phrasing and data interpretation. This continuous reflective practice helped mitigate undue influence of the researcher's own experiences (e.g., as a former marine policy advisor) on participant responses (Morse et al. 2002).

Data triangulation Beyond interviews, the analysis incorporated multiple data sources. Official documents—such as the OCAT TCO System Operation Guideline (OCAT 2021), which outlines the system's operational procedures, related statutes, and governmental reports—were reviewed alongside international MMO system guidelines (e.g., Duarte et al. 2021; Moretti & Affatati 2023) and secondary literature to corroborate interview findings. The credibility of the thematic interpretations was enhanced by cross-referencing participants' accounts with these external sources (Creswell & Poth 2016).

Member checking After initial coding, each participant received a summary of the themes generated from their interview. They were asked to confirm whether the summary accurately captured their views and to provide any clarifications or corrections. Five participants returned feedback, two of them asked for minor adjustments to the wording, and three confirmed its accuracy. All feedback was integrated into the final analysis to ensure fidelity to participant perspectives (Guba & Lincoln 1988; Naeem et al. 2024).

Inter-coder reliability assessment To further bolster internal reliability, two researchers independently coded each transcript using NVivo 12. A preliminary codebook was developed based on grounded-theory principles (Luo et al. 2024) and existing literature on MMO frameworks. Following an initial coding session, the coders met to compare code assignments and calculate inter-coder reliability by using Cohen's kappa. The kappa coefficient exceeded 0.78, indicating substantial agreement (Armstrong et al. 1997; O'Connor & Joffe 2020). Discrepancies were resolved through discussion until consensus was reached on all coded segments.

Thematic analysis and case identification

Once reliability checks were complete, the team conducted a thematic analysis (Braun & Clarke 2006) to identify patterns and categories across interviews. First, open coding generated 37 initial codes reflecting operational challenges, training gaps, regulatory ambiguities, interagency communication barriers, and workforce sustainability concerns. Second, axial coding clustered these codes into 15 sub-themes (e.g., "Insufficient practical training hours," "Lack of enforcement authority," "Fragmented resource sharing," "Career instability for COs"). Finally, selective coding distilled these sub-themes into four overarching themes: (1) Maritime Construction Supervision; (2) Training Curriculum and Certification Standards; (3) CO Employment and Career Pathway; and (4) Cross-Department Resource Integration.

Independent case analyses were extracted from transcripts to illustrate each theme. For instance, one CO described a near-miss incident involving the approach of a disguised cetacean:

"During a piling operation in 2022, the alert zones failed to take into account local current shifts, and a Sousa chinensis surfaced within 200 m. In the absence of underwater detection equipment, reliance was placed solely on binocular observations. On that day, the noise levels soared to 170 dB, more likely causing hearing stress. After this incident, I realized that our training had never covered dynamic current mapping." (Participant C) These verbatim excerpts have been coded and linked to broader policy and guideline commentary.

Limitations and mitigation measures

Although purposive sampling ensured expertise, it may have excluded fringe perspectives (e.g., small-scale fishers unaffiliated with NGOs). To mitigate this, data triangulation with documentary evidence provided a broader context. Additionally, as the interviews were conducted over a six-month period, evolving policy changes (e.g., OCAT's revised guidelines in early 2023) may have influenced participants' reflections. This issue was addressed by noting policy updates during each interview and by explicitly asking participants how adaptation to the new regulations occurred. Finally, given that only seven potential participants completed interviews, some stakeholder voices (e.g., developers who declined participation) remain underrepresented. Future research should aim to include these missing viewpoints to further validate and refine TCO system recommendations.

Results and discussion

Interview design

Interviewees

The interviewees of this study are TCOs, contractors, marine conservationists, and marine experts. Purposive sampling was used; suitable interviewees were sampled by the researcher subjectively for collecting, compiling, and validating the information (Table 1).

Interview outline

This study adopted a semi-structured interview to avoid bias. This study gave the interviewees pre-selected questions. During the interviews, the researcher asked the interviewees for permission to record the conversation. Table 2 presents the interview outline.

Analysis of the interview

Analysis of information from the interview

This study analyzed comments from the interview according to the three steps of the grounded theory: open coding, axial coding and selective coding (Guo et al. 2024). The wording was corrected by editing the open coding to get closer to the original ideas of the interviewees. To get even closer to the

Table 1 Interviewees

Code	Occupation	Years of experience	Job description
A	TCO	3 years	Cetacean monitoring at OWP pile driving
B	TCO	1 year and 2 months	Same as above
C	TCO	1 year and 2 months	Same as above
D	TCO	2 months	Same as above
E	Contractor	1 year and two months	CO hiring, managing, and training
F	Marine conservationist	15 years	Marine ecosystem conservation initiatives and research
G	Expert	20 years	Marine ecologist

Table 2 Interview outline

Number	Question
1	Do you think the current TCO system can effectively supervise developers in implementing various mitigation measures? Any suggestions?
2	Do you think the current TCO training system is comprehensive? Any suggestions?
3	Do you think the current TCOs' career development is comprehensive? Any suggestions?
4	Do you think the current TCO system, the public or private sectors (including the Ocean Conservation Administration, the Environmental Protection Administration, COs, contractors, and training agencies) coordinate well? Is related information available to the public? Any suggestions?
5	What should we do to improve Taiwan's CO system?
6	Any other suggestions?

original ideas of the interviewees, the content was worded again for axial coding. Finally, axial coding was used for selective coding (Guo et al. 2024).

Interview results and analysis

The grounded theory was used to analyze the process of collecting information from the seven interviews. The first step was open coding, and 37 open codes were generated. The second step was axial coding, and 15 codes were generated. In the last step, the 15 axial codes were classified into four categories (Table 3). About the TCO system's current condition, a total of 15 issues required attention, including a lack of supervisory energy and restricted CO power. From the axial codes, this study extracted four selective codes: (1) maritime construction supervision, (2) training systems, (3) career development, and (4) cross-department resource integration. They are explained as follows.

Maritime construction supervision A. *Lack of government supervisory energy*: Regarding on-site inspection, the interviewees suggested that even when the frontline COs are inquired, they are reluctant to report violations due to pressure from developers. Regarding real-time monitoring and penalties, the interviewees said that it is impossible for government departments to fully monitor and receive reports of violations in real time, and penalties are difficult to effectively curb developers' violations.

> "In terms of supervision, COs are under pressure. I don't think the government authority is very efficient in the relevant inspection. I've only seen the EPA and the fisheries department come a few times in the past three years, and they're just on the shore. They didn't ask us questions directly, and even if they did, I didn't dare to say anything bad. There is no way to find out what's the problem." (A 01–01).

b. *Restricted CO power*: All interviewees mentioned that: 1) the COs have the right to suggest but don't have the power to enforce it, b) the CO's report is prepared by the developer, so it is difficult to report violations, c) the relationship between COs and the developers are direct/

Table 3 Selecting coding

Selecting coding	Axial coding	Number of people
Maritime construction supervision	(1) A lack of government supervisory energy	3 people
	(2) Restricted CO power	7 people
	(3) Doubtful CO qualification and certification	2 people
	(4) A lack of items under regulations	2 people
	(5) A lack of species for protection	2 people
	(6) A lack of other mitigation measures	2 people
Training system	(7) A lack of training curricula and insufficient training hours	1 person
	(8) No level-based retraining system	6 people
	(9) No fair and just training completion standard	6 people
	(10) Unfair and impractical training completion certification	6 people
Career development	(11) High barriers of entry	3 people
	(12) Unstable income and benefits	6 people
	(13) Limited development in future	3 people
Cross-department resource integration	(14) Poor public–private sector coordination, non-transparent information, poor resource integration	7 people
	(15) TCO association feasibility	7 people

indirect employment, and the interviewees suggest that under the pressure from the developers, it is almost impossible for COs to report any developer's violation because they do not want to lose their job.

> "To developers, we currently have only the right to suggest. In addition, my contractor is the subcontractor of the developer, who compiles the information and submits the report. There is no way I could report their violations." (B01-02).
> "The records generated by COs are given to the developer for compilation. I am paid by the contractor, and the contractor is paid by the developer. In other words, the developer is my boss. When I do my job and record information, what the developer wants is more important than what the government wants. Although the government authority has set up a whistle-blower system, it is easy to find out who is the whistle-blower in a closed work environment." (C01-02).

c. *Doubtful CO qualification*: Since the TCO system is a novel system and the number of TCOs is insufficient to meet the demand, the TCO System Operation Guideline are MMO certified by The Joint Nature Conservation Committee (JNCC). However, due to the impact of the pandemic in 2019, some foreign courses were taught online, so they did not provide practical maritime assignments. Moreover, the laws and regulations, the monitoring guidelines, the types of maritime construction, and the marine ecosystems vary from country to country, but the TCO system does not address these differences.

> "My situation is unique. The current TCO system recognizes equivalent qualifications, and my contractor and I find the JNCC certificate to be more valuable than TCO certificate because the JNCC certificate is cheaper and offers online courses. The JNCC certificate is recognized worldwide that is why I get the MMO certificate from JNCC. However, there is one disadvantage; it does not provide practical experience in maritime affairs like Taiwan. Moreover, the UK's laws and regulations, the monitoring guidelines, the types of maritime construction, and the marine ecosystems may differ from those of Taiwan's." (D02-03).

d. *Fewer constructions under regulation*: According to the current TCO System Operation Guideline, COs are only required for OWP pile driving, but the interviewees mentioned that other constructions such as bridge construction, seismic exploration and underwater demolition may also have negative impacts on cetaceans. Therefore, the TCO system should have more types of maritime constructions under regulation and develop standards and regulations for those constructions.

> "The MMO system of other countries covers not only pile driving but also bridge construction, seismic exploration, underwater demolition, dredging, and any maritime constructions that produce underwater noise. Taiwan should take similar measures to protect cetaceans more completely." (F03-04).

e. *Fewer protected species*: Currently, the TCO System Operation Guidelines only focus on cetaceans. However, some studies have shown that underwater noise may affect other species, such as sharks and sea turtles. Therefore, it is recommended that the TCO system include turtles and other marine animals.

> "The current system only protects cetaceans, but sea turtles are important animals that need to be protected, and Taiwan has many sea turtle species. As a result, my suggestion is to protect more endangered marine animals that are affected by underwater noise." (F08-05).

f. *Other mitigation measures needed*: According to the interviewees, Passive Acoustic Monitoring Operator (PAMO) and Underwater Noise Monitoring Operator Training (UNMO) are two important and common measures adopted in Taiwan. The former is an auxiliary measure to be taken when the crew is not in good condition to monitor, while the latter is used to monitor underwater noise generated by construction. It is recommended that OCAT include COs in the TCO system and establish a system for training and qualifying COs.

Currently, there is a lack of training/qualification systems for TCO guidelines, as well as a lack of standard operating procedures. It is recommended that OCAT add PAMO to the regulation. PAMO is a commonly used monitoring system internationally.

Training system A. *Suboptimal curricula and insufficient teaching time*: The majority of interviewees think that the current TCO training system is more suitable for novice COs than in other countries. One interviewee suggested that the current teaching time is too short for a CO training qualification. The educational and work experience requirement for those interested in CO training, teaching hours should be increased.

> "The CO is a highly specialized profession. The training courses listed in OCAT's TCO System Operation Guideline cover both classwork instruction and practice at sea, but I do not think 18 to 20 h of training is enough for a person to have all the necessary knowledge and skills and become a qualified CO. Therefore, it is advisable to increase the training time, or set the educational or work experience requirements for the trainees." (B02-07).

b. *No graded retraining system*: Based on the level of experience, the majority of interviewees suggested that the government should set up a retraining system in which experienced COs would mentor novice CO. The interviewees suggested that experience and competencies differed, and that there was a need for a grading system of competencies (e.g., beginner, intermediate, advanced) and the position of a CO should depend on the level indicated on the TCO certificate. In terms of the retraining system, the interviewees suggested that COs have a high turnover rate, and that COs should be retrained and tested regularly in order to ensure that cetacean observers remember what they have learned and update them in a timely manner to be competent in Cos.

> "It's good to have an experience-based system. The ideal is for an experienced CO to work with novice a CO. Considering that wind farms are getting bigger and that CO is still an emerging profession, it is impossible to find many experienced Cos. I think it is not feasible until the system is more full-fledged."

c. *Lack of uniform or fair standards for training completion*: Despite the fact that TCO training providers have rules in place to achieve OCAT certification, the interviewees indicated that there is a lack of uniform standards for TCO assessment. It is important to note that the examiners are civil servants and sometimes do not even show up to supervise the exam, which explains differences in TCO capabilities.

> "Students are almost guaranteed to pass the qualification assessment. My training institution is also my contractor, and the examiners are hired by the company, so it is impossible for the trainee to fail; This also explains the difference in the abilities of the trainees." (C02-09).
> "Regarding evaluation and certification, I think the examiners should be appointed by the government, and we need a unified evaluation system and standard. The certification should be issued by the government authority with a set expiration date. COs must be retrained and assessed on a regular basis. These are essential to maintain the competence and professionalism of the CO." (G02-10).

d. *Unfair certification of training completion and inadequate practical applicability*: The interviewees believed that the current TCO training evaluation system is flawed. A certificate authority does not issue certificates on behalf of the government authority. Hence, the fairness of the TCO certificate is questionable. Moreover, Taiwan's TCO certificate is not recognized in other countries and costs more than obtaining an equivalent certificate in other countries.

> "As for the certificate, I think it is best to issue them as if they were in other countries. While the training provider is accredited by OCAT, the issuing body is the training provider itself, not the government authority. I think this leads to an unfair certificate and a lack of universality." (C02-10).
> "Regarding the evaluation and certification, I think the government should appoint the examiners. There is also a need for uniform evaluation systems and standards. The certificate should be issued by the government and should be valid for a certain period of time. The COs should be retained and evaluated regularly to maintain their professionalism and competence." (G02-10).

Career development A. *High barriers to entry*: For COs, the interviewees explained that they must have several certificates, including the TCO certificate, the seafarer certificate, the GWO (Global Wind Organization) training certificate, and the EMT (emergency medical technician) certificate. Moreover, the training for such certification is expensive, and require regular retraining. Depending on the requirement of the wind farm's environmental impact assessment, the types of certificates needed may vary. Consequently, the high cost of obtaining professionally qualifications for different wind farms is prohibitive.

> "I think the bar for CO is high. CO training, as well as some other seafarer safety training, wind power training and emergency training and other certifications, cost about NT$100,000 or more, and the validity period is limited. Usually, we need to be subsidized by the company or the company bears this part of the cost." (E03-11).

b. *Unstable income and benefits*: COs work at the sea, and their income depends on the weather, sea states, and whether pile driving is smoothly. The income of CO varies from contractor to contractor and varies from year to year depending on the competition in the market. The interviewees pointed out that some COs are daily wages (no base salary), while others may have a base salary and additional benefits. Since the piling time is from April to October, the contracted CO only earns six months per year, and there are no year-end bonus or other benefits. They need to find other jobs during winter, and there is no guarantee that their contract will be renewed the following year because their contractor may not be able to win the CO contracts. Consequently, with the exception of a few COs who are full-time and have a base salary, the income and benefits of most COs are not stable compared to other professionals.

> "Regarding the entry barriers, the income and benefits, the working hours, and the work shifts, I heard that it

> varies depending on the wind farms and the contractors. Due to the non-disclosure agreements, it is difficult to judge whether the work environment is good or bad." (F03-12) Moreover, "Since contractors and developers hire COs, some contract coordinators will get a good quote and some won't. Due to the practice of signing non-disclosure agreements, it is difficult to judge whether an offer is appropriate." (G03-12).

c. *Limited career development*: The interviewees had the most diverse views on the issue, but all expressed high concern about the development of COs in Taiwan, especially with a focus on shrinking market demand and the unstable income. Four interviewees suggested that if the government is determined to develop the CO system, it should make COs mandatory for more types of maritime construction, increase the animal species to be protected, and incorporate maritime tourism and animal conservation activities into the system to increase employment opportunities for COs, improve the income and benefits for COs, and help them accumulate work experience to boost the potential of this profession.

> "I think the CO is an unpromising profession in Taiwan, because the emerging profession of TCO is based on the country's OWP policy. However, the construction of offshore wind turbines will eventually end one day. So, while the lecturer mentioned the possibility of future wind turbine maintenance, and the needs for cetacean monitoring or related statistics, I doubt how many COs will be able to continue in the industry. The job market is especially gloomy for those who later obtain their CO certificates." (B-03–13).

Cross-department resource integration A. *The coordination mechanism between the public and private sectors is inadequate, leading to insufficient transparency of relevant information and a lack of integration of resources*: The TCO system involves many government departments and laws and regulations. The interviewees indicated that current OCAT and the CO system do not effectively integrate resources and information from public and private sectors. Although there is a dedicated OWP section on the OCAT's website, the interviewees reported that there is not enough information to be called a one-stop, fully integrated platform. This is a key reason for the lack of interaction and openness in the CO industry, which can affect the supervisory power, the training system, and the career development for COs.

> "I am basically a frontline CO at the wind farm. The communication between the public and private sectors is usually handled by a full-time employee of the contractor or the developer. If I have a problem, I will report it to the contractor. This field is too closed, and it is difficult to find related information. In fact, I do not know whom to ask for help, so I simply follow the contractor's or developer's instructions." (C04-14).

b. *Establishing a TCO association to improve the TCO system*: Regarding the establishment and operation of the association, the interviewees believed that an important strategy is to ensure the comprehensiveness of the system, and they provided the following ideas: (1) Include COs and people from the industry, the government, the schools, and other professions to discover problems through meetings and forums and gradually establish and improve the existing system. (2) Establish a third-party organization to conduct independently, effectively, and fairly in order to prevent developers from putting COs under stress, and to establish a complete training system and CO work environment. (3) Participation in marine ecosystem protection activities, such as protecting and rescuing cetaceans, beach cleaning, and educational guided tours, etc. Another good idea is to work with the government and public interest groups to increase the visibility of the association and gain social acceptance. (4) Through the above methods, it has been recognized by the government, CO operators, public welfare organizations and the public.

> "I would suggest the association provide a communication platform for public and private sectors. The association can also consult its members for suggestions and feedback and provide training and employment services. I think that in this way, the government can get suggestions for improvement, and the association can also make rules related to the system for companies and workers to follow. The association will support COs to enable them to supervise effectively, and to establish a complete training system and a good work environment." (D-07–16).

The results of the in-depth interview are consistent with the results of the literature review. They all agree that the current TCO system needs to be improved urgently, including maritime construction monitoring, the training system, career development, and cross-department resource integration (Fig. 8).

Conclusion

Conclusion

Through an in-depth review of Sects. "Acoustic propagation and species-specific impact assessment, "Noise mitigation effectiveness and cumulative noise impacts", "Real-time passive acoustic monitoring and shut-down systems" and Ecosystem-level long-term effects", covering acoustic propagation and species-specific impact assessment

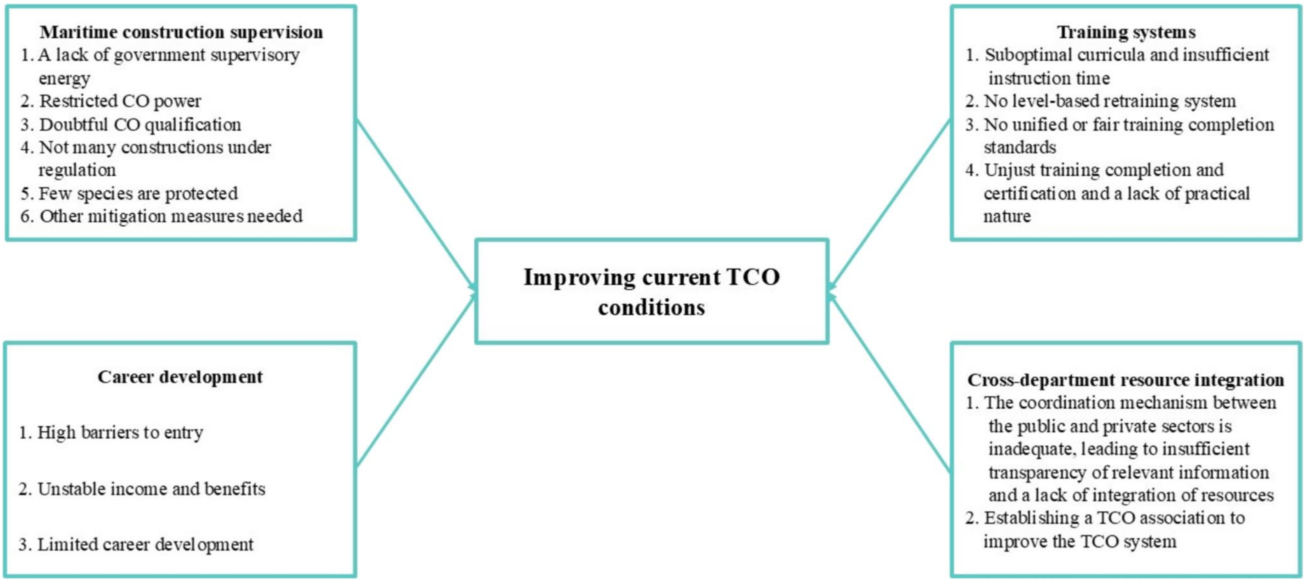

Fig. 8 Issues related to the current Taiwan cetacean observer system

(Jensen et al. 2011; Hildebrand 2009; Rolland et al. 2012; El-Dairi et al. 2024), noise mitigation effects and cumulative impacts (Cefas 2015; Bellmann et al. 2020; Kim et al. 2025), real-time PAM and shutdown protocols (Gillespie et al. 2013; Macrander et al. 2021; Thode et al. 2021), and long-term impacts at the ecosystem level (Fanelli et al. 2022; Merchant et al. 2022)—this study has identified critical institutional, operational, and legal gaps in TCO system.

First, the scope of this work is explicitly clarified as follows: This research evaluates Taiwan's CO legal, policy framework, rather than conducting new ecological modeling or physiological measurements. Although detailed site-specific propagation models (e.g., those using multi-layer sound-speed profiles and ray-tracing algorithms) and biomarker assays are indispensable for precise acoustic impact assessments and ecological understanding, they lie outside the scope and mandate of this policy-focused study.

Second, the literature review demonstrated that advanced tools and methods—such as high-resolution insertion-loss simulations for assessing bubble-screen curtain efficacy (Cefas 2015), PAMGUARD-enabled real-time detection and localization of cetacean calls (Gillespie et al. 2013), and PCAD frameworks linking noise exposure to demographic declines (Pirotta 2022)—can directly inform TCO operational thresholds, training courses, and legal definitions of harmful noise. Policy recommendations draw on the latest scientific evidence, integrating research findings in acoustic modeling, noise mitigation, PAM protocols, and ecosystem-level assessments.

Third, our comparative and interview-based analysis revealed systemic challenges:

- Supervisory Authority Deficits: OCAT's current regulations lack clear enforcement powers to independently gather noise data or issue stop-work orders based on acoustic thresholds derived from insertion-loss models (Rolland et al. 2012).
- Lack of reporting independence: Developers continue to submit monitoring reports through contractors, undermining data integrity and transparency (Oros et al. 2024; Louropoulou et al. 2025).
- Operational Monitoring Gaps: Without real-time PAM integration (Gillespie et al. 2013; Macrander et al. 2021), TCOs is not able to detect and respond to the presence of cetacean in a timely manner during pile driving or turbine operation.
- Inconsistent Training and Certification: Existing curricula ignore key competencies—such as interpreting ray-traced propagation outputs (Jensen et al. 2011) or understanding cumulative stress biomarkers (El-Dairi et al. 2024)—and lack standardized re-certification processes.
- Fragmentation of Career and Resource: High barriers to entry and lack of a centralized TCO Association hinder professional development; Siloed information platforms hinder interagency collaboration and public participation.

Overall, these findings highlight the urgent need for a TCO system in Taiwan to be aligned with scientific best practices and international policy frameworks (Kusuma & Putra 2024; Galgani et al. 2024; SDG 14) is in line with each other. Moving forward, collaboration with marine ecologists will be essential to integrate model-derived risk zones and stress-marker thresholds into practical observer guidelines and training modules. These interdisciplinary collaborations will ensure that TCOs operate on a foundation of robust acoustic science while fulfilling their policy mandate.

Suggestions

A comprehensive and detailed set of recommendations follows. Each recommendation is based on empirical interview findings and incorporates best practices in the international MMO systems, and aims to support Taiwan's transition to a legally robust, technologically advanced, and ecologically informed TCO regime.

Maritime construction supervision

To bridge the gaps in enforcement and operations, amend the Marine Conservation Act to explicitly authorize OCAT to appoint COs. Grant OCAT independent data-collection rights and legal authority to classify harmful underwater noise as ocean pollution. This authorization will enable TCOs to intervene immediately to issue a stop-work orders when acoustic levels exceed biologically relevant thresholds such as 160 dB SPL for mid-frequency cetaceans (Hildebrand 2009; Rolland et al. 2012). This is consistent with enforcement mechanisms observed in U.S. and Canadian frameworks (Louropoulou et al. 2025).

Establishing a centralized, real-time monitoring platform integrating AIS vessel tracking, weather data, and PAM data is also recommended. The system would enable OCAT and other regulators to track compliance and identify violations immediately. Drawing on the EU's Marine Strategy Framework Directive and the U.S. National Marine Fisheries Service database protocols, a legal digital noise-log transmission format is proposed to ensure standardized metadata reporting and transparency (Oros et al. 2024; Louropoulou et al. 2025; Funk et al. 2024a, b).

To enforce model-based predictions, a joint inspection should be conducted using OCAT-EPA mobile patrols equipped with PAM units. Real-time comparisons of on-site noise levels with propagation model outputs will help to dynamically adjust the radius of the warning area and implement mitigation measures immediately (Bellmann et al. 2020). These proposals provide legal and technical mechanisms for the implementation of acoustic science in the regulatory field.

Training system enhancement

Three levels of certification courses are offered: Beginner (40 h), Intermediate (60 h), and Advanced (80 h). These modules will cover acoustic propagation modeling, real-time PAM techniques, legal definitions of harmful noise, and the ecological impacts of stressors on cetacean populations. Retraining (20 h) every two years is recommended, based on the UK JNCC and EU MMO frameworks, to ensure trainees' skills remain current (Martin et al. 2023; Moretti & Affatati 2023). The assessment will be conducted by OCAT-appointed public examiners, and will be supervised by an independent third-party agency, such as a newly established TCO Association. This system will not only make the certification process more professional, but will also enhance public trust and international comparability (Yang & Wang 2022).

Career development for cetacean observers

Interviews revealed that many COs face job instability due to project-based contracts and limited opportunities for career development. To address this issue, the existing qualifications should be consolidated into a unified "Marine Acoustic Observer" credential, thereby reducing overlap among TCO, GWO, and EMT certifications. Citing on the European fisheries cost-sharing schemes, this integration could reduce training costs by 30% and total instructional time by 20% (Oros et al. 2024; Louropoulou et al. 2025).

Establish a career portal maintained by OCAT that lists open CO positions and training activities, and provides labor-market data such as salary benchmarks and demand forecasts. This portal would also publish an annual "State of TCO" report to help stabilize the industry and attract qualified candidates.

To broaden the scope of work and reduce underemployment, COs should engage in seismic survey oversight, port dredging monitoring, marine tourism, and biodiversity assessments. These roles will help COs diversify their income streams while supporting Taiwan's marine spatial planning goals (Duarte et al. 2021).

Cross-department resource integration

Fragmented databases and siloed monitoring systems remain major obstacles. It is proposed that a unified web-based platform be developed, incorporating training resources, real-time PAM dashboards, alert-zone maps, and a legal document repository (OCAT, 2022a). The portal draws on the UK's JNCC-MMO model, and will also include a knowledge-sharing forum for TCOs, developers, and researchers.

The establishment of a professional TCO Association is recommended to institutionalize stakeholder coordination. The non-profit organization will be responsible for drafting observation protocols, updating the training modules, and advising OCAT on the list of protected species and the definition of buffer zones in line with UNCLOS and EU Directives (Funk et al. 2024a, b).

These integration mechanisms will improve data transparency, promote public engagement, and align Taiwan's monitoring systems with international marine biodiversity governance standards.

Future research directions

To build on this policy orientation, interdisciplinary collaborations with marine ecologists and acoustic modelers are recommended. Future research work should:

- Develop site-specific propagation models to optimize warning areas using local bathymetric measurements and seasonal sound velocity profiles (Huo et al. 2024).
- Conduct longitudinal biomarker studies to track the physiological stress responses in marine mammals and validate model-based risk thresholds (El-Dairi et al. 2024).
- Assess the cumulative impacts of noise, chemical pollutants, and climate change on the resilience of marine ecosystems (Barron et al. 2021).
- Quantify ecosystem services affected by underwater noise (e.g., fisheries productivity, carbon sequestration), and translate ecological indicators into economic terms to support cost–benefit assessments (Clark et al. 2009).
- Based on standards from the EU and the U.S. National Oceanic and Atmospheric Administration (NOAA) (Faulkner et al. 2018; Louropoulou et al. 2025), which define legally binding thresholds for Good Environmental Status (GES) based on Taiwan's equivalent of MSFD Descriptor 11,

By implementing the above suggestions and establishing future interdisciplinary studies, TCO system can be developed into a world-class model of environmental governance—ecologically sound, legally defensible, and institutionally resilient.

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Authors' contributions N. T. Chiang and R. H. Kao contributed to the conception and design of the study and further reviewed and edited the manuscript. The material preparation, data analysis, and original manuscript drafting were performed by N. T. Chiang and Chun-Kai, Huang., R. H. Kao and C. K. Huang conducted the research investigations and data collection. Corresponding author R. H. Kao is the responsible supervisor. All the authors have read and approved the final manuscript.

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Data availability Data will be made available upon request.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval All procedures performed in this study involving human participants were conducted under the guidance of the supervising professor in accordance with the Ministry of Education of the Republic of China's research ethics regulations (Master's thesis exempt from formal review) and with the 1964 Helsinki Declaration and its later amendments or equivalent ethical standards; compliance was confirmed by the oral examination committee at the Master's thesis defense. Ethical approval: This article does not contain any studies with animals performed by any of the authors.

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