**Proceedings of the ASME 2023 42nd International Conference on Ocean, Offshore and Arctic Engineering**
**OMAE2023**
**June 11-16, 2023, Melbourne, Australia**

**OMAE2023- 104358**

# ASSESSING UNDERWATER NOISE IMPACT FROM MARINE PROJECTS

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## ABSTRACT

*A substantial number of marine infrastructural projects result in increased environmental impact on marine fauna during the construction and operational stages of the projects. A significant part of this impact is due to excessive noise. The absence of standard methods of underwater noise assessment and prediction increase the risk of unacceptable change to the marine environment as a result of offshore anthropogenic activities. Generally, the auditory systems of marine species are different from that of humans, however it is typical to attempt to extend the same approaches as used for human settings to marine ecosystems. The justification of such approaches is not provided, however it is well understood from a practicability perspective.*

*Construction operations such as pile driving and dredging may result in significant noise increase and irreversible impact on marine species. This paper reviews relevant regulatory documents and summarizes considerations that are typically used to setting relevant underwater criteria for construction and operational noise. It also suggests approaches to groups of acoustic criteria that may be used to control and minimize underwater noise impact.*

*General methods of modelling underwater noise impact are reviewed as a part of planning for marine projects and identifying the need for noise mitigation measurements and preparation of relevant construction and operation plans. These approaches may be used to identify relevant noise criteria and submit environmental effect statements to attain regulatory approvals.*

Keywords: underwater noise, marine species, peak sound level, rms sound level, permanent threshold shift, temporary threshold shift, sound exposure level.

## NOMENCLATURE

Place nomenclature section, if needed, here. Nomenclature should be given in a column, like this:

| | |
|---|---|
| $L$ | root mean square sound pressure level, dB |
| $L_{peak}$ | peak sound pressure level, dB |
| $p_{peak}$ | peak acoustic pressure, Pa |
| $p_{rms}$ | root mean square acoustic pressure |
| $p_{ref}$ | reference acoustic pressure in water, 1 μPa |
| $p(t)$ | acoustic pressure, Pa |
| $p_0$ | static pressure, Pa |
| SEL | sound exposure level, dB |
| $T$ | averaging period, s |

## 1. INTRODUCTION

Construction of offshore infrastructure may be accompanied by high impact on marine flora and fauna. Underwater noise impact from such projects may be either long lasting or be short term and confined to the construction phase of the project only. The existing underwater ambient noise environment at a given location is a complex composite of natural non-biological, biological and anthropomorphic noise sources. The range of acoustic frequencies associated with these noise sources varies considerably, from low frequency sounds in the order of 10 cycles per second (10 Hz), such as that produced by the blade-pass frequency of a large ship, to very high frequencies in the order of a hundred thousand cycles per second (100 kHz) associated with phenomena such as small bubble resonance or dolphin echo location clicks.

Natural non-biological sources of underwater noise in the area are anticipated to be from wave turbulence, waves breaking along shorelines, wind-wave interactions and precipitation. The contribution from each source depends on the frequencies of interest. Breaking ocean waves, for example, generate acoustic pressure frequencies ranging from less than 1 Hz to greater than 100 kHz [1].

Wenz showed that in the frequency region above 100 Hz, underwater ambient noise levels depend on weather conditions, with wind and waves creating sound [2]. At frequencies above 100 Hz, distant shipping noise makes a significant contribution to the noise levels in almost all of the world's oceans. In the mid-frequency range (10 kHz), sediment transport noise may be a significant noise source where strong currents and turbulence exist due to wave action or tidal flow. At frequencies greater than 50 kHz, the molecular motion of water (thermal noise) contributes to the ambient noise level at an increasing rate [3].

In general, anthropogenic sources of underwater noise in an area can vary. Industrial and recreational activities (such as boating and jet skiing) or boat traffic are examples of such noise sources. Ports can be considered as typical "hot spots" for long term underwater noise impacts. Construction activities accompanied by high levels of underwater noise may last several years and lead to irreversible changes in the affected area.

## 2. CHARACTERISTICS OF UNDERWATER NOISE AND MARINE FAUNA

In the context of acoustic reception and communication by marine fauna, the potential impact of underwater noise requires an understanding of the type and acoustic spectrum of the noise source relative to the sensory frequency range of the marine fauna of interest. In general, the hearing range for marine fauna is very wide. For example, marine mammals have a typical hearing range from a few Hertz (low- frequency cetaceans) to approximately 160 kHz (mid- and high- frequency cetaceans).

### 2.1 Noise sources and their characterization

Underwater noise sources can be broadly classified as either impulsive or non-impulsive. The US National Marine Fisheries Service (NMFS) provides the following definitions [4]:

— Impulsive - Sounds that are typically transient, brief (less than 1 second), broadband and consist of high peak sound pressure with a rapid rise time and rapid decay. Impulsive noise sources can be single pulse (e.g. single explosion, impact pile strike, sonar ping, etc.) or multiple pulses (serial explosions, multiple pile strikes, etc.).

— Non-impulsive - Sounds that can be broadband, narrowband or tonal, brief or prolonged, continuous or intermittent and typically do not have a high peak sound pressure with rapid rise and decay times. Examples of non-impulsive noise sources include ship pass-by's, rock dumping, drilling, etc.

The distinction between impulsive and non-impulsive noise sources recognizes the fact that impulsive noise sources have sound characteristics that make them more injurious to marine fauna than non-impulsive sources. This is similar to health effects on humans. Since noise effects on humans have been intensively studied, many analogies used in assessing the noise impact on people are also utilized for marine projects. It is also reflected in acoustic metrics used for predicting and measuring the noise impact on marine fauna.

Instantaneous peak pressure is used to assess underwater noise, as possible damage from impulsive noise sources does not necessarily depend on the duration of exposure. The recognition of peak pressure impacts on marine fauna developed from studies of the effects of underwater explosions and seismic array impulses on marine fauna. The instantaneous peak pressure ($L_{peak}$) generated by an outward radiated pressure pulse is measured to assess the risk of immediate physical damage to auditory tissue/structures, vascular structures or damage to air filled cavities such as fish swim bladders. The most severe possible impact of peak pressure pulses on marine species is mortality.

For continuous noise, the total or accumulated acoustic energy and frequency content of the underwater acoustic energy over a period of time is often quantified to assess the potential cumulative auditory damage effects to marine fauna. This requires evaluation of the root mean square (rms) pressure magnitude.

Both peak ($L_{peak}$) and root mean square ($L$) underwater sound pressure levels are defined from the instantaneous fluctuating pressure ($p(t)$) during measurement period $T$, the static pressure ($p_o$), and a reference pressure ($p_{ref}$) of one micro Pascal (acoustic reference in fluid medium):

$$L_{peak} = 10 * log_{10}\left(\frac{p_{peak}^2}{p_{ref}^2}\right), \text{ where } p_{peak} = max|p(t) - p_o|$$

$$L = 10log_{10}\left(\frac{p_{rms}^2}{p_{ref}^2}\right),$$

$$\text{where } p_{rms} = \sqrt{\frac{1}{T}\int_0^T (p(t) - p_o)^2 dt}. \quad (1)$$

Previously, the potential impacts of underwater noise on fauna from infrastructure projects were primarily understood in terms of the potential immediate physiological damage associated with instantaneous peak pressures close to the noise source, or a short-term behavioral disturbance. In the last decade, the potential for cumulative noise impacts from noise sources (such as multiple pile strikes) has also been recognised. The meaning of cumulative in this context is the additive noise exposure effect of many successive impulsive events (such as pile strikes). A key potential impact of concern (among others including temporary displacement) is the temporary loss of auditory sensitivity of marine fauna. This process is analogous to the temporary loss of hearing sensitivity in humans that are exposed to excessive accumulated noise over a period of time.

The sound exposure level (SEL) is used to measure the total acoustic energy of the underwater noise over a period of time. The SEL is defined as the product of the level and time, accumulated over a time interval or event as follows:

$$SEL = 10log_{10}\left[\int_0^T \left(\frac{p(t)^2}{p_{ref}^2}\right) dt\right]. \quad (2)$$

The relatively recent consideration of cumulative noise impacts has greatly increased the size of the potential noise-affected zone surrounding a piling operation in which adverse fauna impacts may occur compared with peak pressure considerations only. As a consequence of this improved understanding of cumulative noise impacts, significant effort has been directed at developing and implementing noise mitigation measures.

## 2.2 Noise sources and their characterization

Different species of marine fauna have different hearing sensitivities, depending on the evolutionary structure of the hearing organ. In recognition of these differences, research has focused on the creation of audiograms (measures of hearing sensitivity versus frequency) to better understand the hearing ranges of marine fauna. These audiograms have been used to derive frequency-weighting functions for some marine fauna. The frequency weighting functions are similar to the weighting functions developed for the human ear and recognise the fact that the ear is not equally sensitive to noise at all frequencies. The hearing sensitivities of individual species are discussed below.

### 2.2 .1 Marine mammals

Southall et al. developed a comprehensive set of frequency-weighting functions for marine mammals [5]. Citing previous scientific literature, they used the following mammal hearing-groups: low frequency cetaceans (baleen whales), mid frequency cetaceans (toothed whales), high frequency cetaceans (porpoises, river dolphins, etc.), pinnipeds (seals, sea lions, walruses, in water) and pinnipeds (in air).

They proposed separate 'M' frequency-weighting functions for these groups, which were similar to the C-weighting function developed for human hearing. These functions were flat for a major part of the spectrum, symmetrical and assumed a logarithmic reduction in auditory sensitivity outside the range of best hearing. The 'M' frequency-weighting functions were a conservative representation of hearing sensitivities based on the scientific literature available at the time.

In the decade following that research, significant additional work has been undertaken in the field. Additional marine mammal groups, modifications to the original groups and new weighting functions (based on audiograms) have been developed. Results of this research has been incorporated into the guidance provided by the US NMFS [4].

Southall et al. (2019) have also revisited their original recommendations and published revised scientific recommendations on the marine mammal noise exposure criteria [6].

The currently accepted marine mammal hearing groups include the following:

- Low-frequency (LF) cetaceans: mysticetes (Baleen whales). The generalised hearing range for this group is estimated to be between 7 Hz and 35 kHz.
- High-frequency (HF) cetaceans: Delphinid species (bottlenose dolphin, common dolphin, beaked whales, sperm whales and killer whales). The generalised hearing range for this group is estimated to be between 150 Hz and 160 kHz.
- Very high-frequency (VHF) cetaceans: true porpoises, most river dolphin species, pygmy/dwarf sperm whales and some oceanic dolphins. The generalised hearing range for this group is estimated to be between 275 Hz and 160 kHz.
- Sirenians (SI): manatees and dugongs. The generalised hearing range for this group is estimated between 250 Hz and 72 kHz.
- Phocid carnivores (in water) (PCW) and in air (PCA): true seals, including harbor, gray and freshwater seals, elephant and monk seals, and Antarctic and Arctic ice seals. The generalized hearing range for this group is estimated to be between 50 Hz and 86 kHz.
- Other carnivores in water (OCW) and in air (OCA): Otariid seals (sea lions and fur seals), walruses, sea otters and polar bears. The generalized hearing range for this group is estimated to be between 60 Hz and 39 kHz.

Revised frequency-weighting functions, analogous to the A-weighting function for human hearing, have been created based on a general band-pass filter equation for each marine mammal group. The band pass filter parameters were derived from audiogram data corresponding to each group.

These frequency-weighting functions are presented in Figure 1 and Figure 2 (referenced from [4]). For phocid carnivores and other carnivores, the presented weighting functions have been limited to the 'in water' categories. The functions are denoted by subscripts corresponding to the group names (LF, HF, VHF, SI, PCW, OCW).

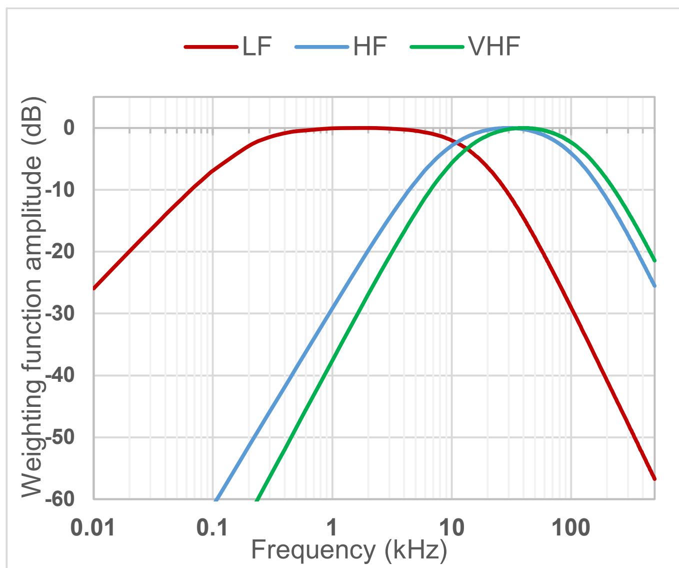


**FIGURE 1:** AUDITORY WEIGHTING FUNCTIONS FOR LOW FREQUENCY, HIGH FREQUENCY AND VERY HIGH FREQUENCY HEARING GROUP CETACEANS

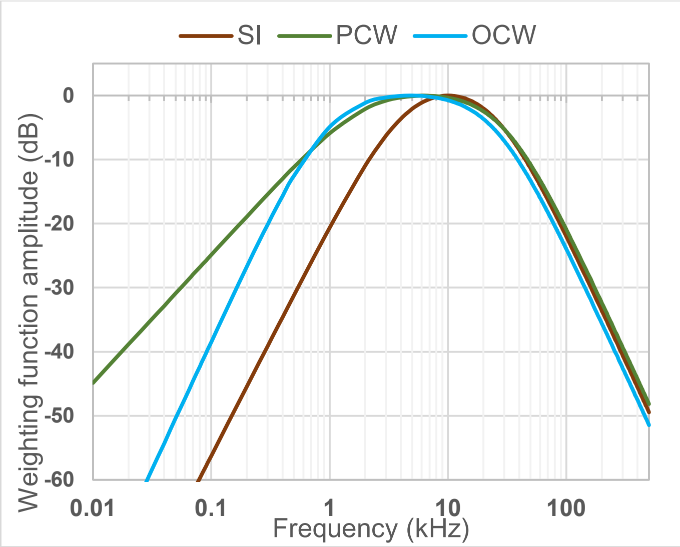


**FIGURE 2:** AUDITORY WEIGHTING FUNCTIONS FOR SIRENIANS, PHOCID CARNIVORES (IN WATER) AND OTHER CARNIVORES (IN WATER)

### 2.2 .2 Fish sensitivity

A few tens of thousands species of fish exist, compared to approximately 130 marine mammals. Fish are much more diverse anatomically, physiologically, ecologically and behaviorally than marine mammals. Hearing range of most fish is currently not estimated.

Research indicates that many fish species respond to the particle motion component of sound waves while marine mammals do not. Particle motion is the oscillatory displacement of fluid particles in a sound field [7] and generally reported with reference to acceleration (m/s2).

Groups of fish can be segregated into a few groups based on their auditory system (Popper at al. [8] ):

- Fishes with no swim bladder or other gas chamber (e.g. dab and other flatfish): These fish only detect particle motion and are less susceptible to pressure-related injuries.
- Fishes with swim bladders in which hearing does not involve the swim bladder or other gas volume (e.g. Atlantic salmon): These fish base their hearing only on particle motion but are susceptible to pressure-related injuries.
- Fishes in which hearing involves a swim bladder or other gas volume (Atlantic cod, herring and relatives, etc.): These fish detect sound pressure and particle motion and are susceptible to pressure-related injuries.

Behavioral audiograms for select fish species sensitive to particle motion are provided in Figure 3 (referenced from [8]), while audiograms for select fish species sensitive to sound pressure are provided in Figure 4 (referenced from [8]).

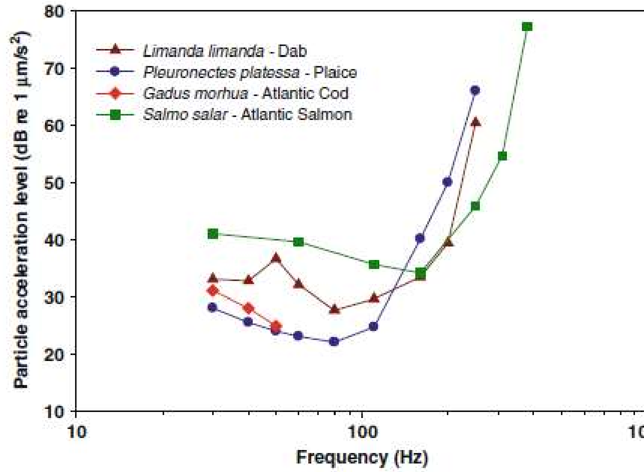


**FIGURE 3:** PARTICLE MOTION HEARING SENSITIVITY FOR SELECT FISH SPECIES

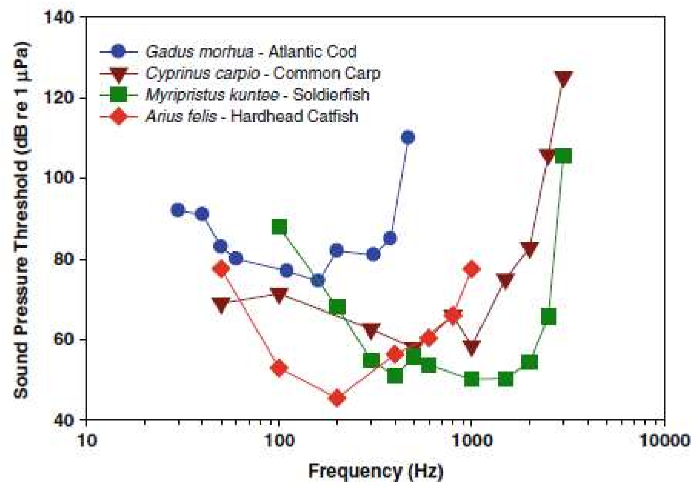


**FIGURE 4:** SOUND PRESSURE HEARING SENSITIVITY FOR SELECT FISH SPECIES

### 2.2.3 Sensitivity of other species

The diversity of marine species and their auditory systems make it difficult to generalize their sensitivity to underwater noise. For example, the auditory frequency range of marine turtles is significantly lower than that of marine mammals, with estimates for a range of species (including the green turtle and loggerhead turtle) in the range of 100 Hz to 1 kHz [9] and best sensitivities at relatively low frequencies near 400 – 1000 Hz [10].

Martin et al. have presented data on the behavioral and auditory evoked potential (AEP) thresholds for the loggerhead sea turtle [11]. This was included in Popper et al.'s recommended sound exposure guidelines for fishes and sea turtles [8].

Data on hearing sensitivity for most other species of turtles is currently limited. However, based on the research undertaken so far, it can be reasonably assumed that the auditory frequency range of marine turtles is between 50 Hz to 1.2 kHz.

Data on the underwater hearing ranges of seabirds (such as penguins) is insufficient and limited for generalization. Most studies extrapolate data from studies undertaken on the hearing of land birds.

On average, bird hearing is estimated to be most sensitive between 2 and 5 kHz (air), with the frequency of best hearing sensitivity potentially shifting to below 2 kHz and 4 kHz underwater [12].

For the great cormorant, Johansen et al. measured hearing sensitivities in air and underwater [13]. Their findings suggest similar hearing frequencies in-air and underwater. The data also shows that an increase in sound energy is required for the cormorant to hear the higher ranges under water, i.e. they are less sensitive to the higher ranges under water (this is typical of the muffled sound experienced in humans when swimming underwater).

## 3. EFFECTS OF UNDERWATER NOISE ON MARINE FAUNA

The effects of underwater noise on marine fauna depend on the magnitude and type of the noise source and the hearing sensitivities of the marine fauna that may be impacted by anthropogenic noise.

In general, the potential impacts of excessive levels of underwater noise on marine fauna may include:

- Significant behavioral disturbance that may affect important populations or species survival
- Noise masking interference with acoustic communication and echo location
- Temporary loss of auditory sensitivity
- Permanent loss of auditory sensitivity
- Other tissue damage (lethal and sub-lethal).

There may be a range of effects from the same activity, e.g. where the marine fauna is close to a sound source (highest intensity), the impact on an animal can include death, physiological effects, temporary hearing shift, masking and behavioral responses [7].

Physiological impacts refer to immediate damage (permanent or temporary) to the auditory system (or other tissues) of the marine fauna. For example, at high sound pressures noise sources such as marine pile driving, explosions and air gun arrays have the potential to damage the auditory structures of fish (soft sensory tissue on the fish's otolith) and rupture swim bladders [14].

As with consideration of the human auditory exposure, the terms temporary threshold shift (TTS) and permanent threshold shift (PTS) are used to describe the physiological impacts on marine fauna.

Temporary threshold shift (TTS) refers to the effect of sudden or cumulative noise exposure causing a temporary loss of hearing sensitivity. This can directly impact the survival of marine fauna, such as dolphins, by diminishing their ability to respond to danger, or by diminishing the acuity of acoustic methods for prey detection, navigation and communication, including mother to calf communication. The duration of TTS varies depending on the nature of the sound and the impacted species.

The term permanent threshold shift (PTS) refers to the effect of the more severe sudden or cumulative noise exposure, causing permanent loss of hearing sensitivity due to tissue damage within the auditory system.

TTS and PTS noise impact criteria for individual species are discussed further in Section 4.

Underwater noise has the potential to adversely affect marine species by inducing behavioral responses. In the context of marine mammal conservation, behavioral responses are defined by Southall et al. as responses that may result in demonstrable effects on individual growth, survival, or reproduction [5]. Examples given for the onset of significant behavioral response include:

- Individual and/or group avoidance of a sound source
- Aggressive behavior
- Startled response (that may expose an individual to danger)
- Brief or minor separation of mother and calf
- Extended cessation of vocal behavior
- Brief cessation of reproductive behavior

The latest guidance from the US NMFS [4] notes that behavioral responses can depend on numerous factors including intrinsic, natural extrinsic (such as ice cover and prey distribution) or anthropogenic, as well as interplay among these factors. In addition, responses can vary not only among individuals but also within an individual.

In relation to noise sources such as marine piling it is often assumed that marine fauna will choose to move away from intense impulsive noise to achieve a better level of auditory comfort. Whilst this assumption would be reassuring from an environmental management perspective as it would provide a basis upon which to suppose that an acoustic hazard zone can be cleared via a soft start piling approach, there is growing evidence that this may not be the case.

Weilgart (2018) notes that some species are territorial and may be guarding their nests [15]. Others may remain at the location due to lucrative environmental conditions (such as food), may not be able to move quickly enough to escape the noise or be frozen in place from fright.

Green turtles have been observed in close proximity to marine impact piling with no observable flight response [16]. For example, it is also well known that marine turtles are sometimes inadvertently caught by the suction head of slow-moving trailing arm suction hopper dredges, which can generate intense noise at the suction head. Some researchers conclude that there is no compelling evidence that a soft start piling approach is effective in clearing fauna from a piling site. Whilst a soft start methodology is deemed to be a prudent one in many cases, the strategic importance of effective surveillance within a defined acoustic hazard zone should not be downplayed once a piling operation has reached normal piling strike energies.

The criteria for cetaceans, carnivores and sirenians are presented in Tables 1 and 2. SEL levels are references to 1 $\mu Pa^2 s$. It should be noted that the classification in accordance with the

Department of Planning, Transport and Infrastructure's (DPTI) Underwater Piling Noise Guidelines [17] refer to high-frequency cetaceans as mid-frequency cetaceans and very high frequency cetaceans as high frequency cetaceans.

**TABLE 1:** BEHAVIOURAL AND PHYSIOLOGICAL NOISE CRITERIA FOR CETACENS -IMPULSIVE NOISE

| Thresholds | Marine species and noise criteria | | |
|---|---|---|---|
| | Low-frequency cetaceans | High (Mid)-frequency cetaceans | Very high (high) frequency cetaceans |
| **Noise criteria, PTS[2] onset threshold** | 183 SEL (Weighted) | 185 SEL (Weighted) | 155 SEL (Weighted) |
| | 219 Peak (Unweighted) | 230 Peak (Unweighted) | 202 Peak (Unweighted) |
| **Noise criteria, TTS[3] onset threshold** | 168 SEL Weighted | 170 SEL Weighted | 140 SEL Weighted |
| | 213 Peak (Unweighted) | 224 Peak (Unweighted) | 196 Peak (Unweighted) |
| **Behavioral** | 160 dB rms (Unweighted) | | |

**TABLE 2:** BEHAVIOURAL AND PHYSIOLOGICAL NOISE CRITERIA FOR SIRENIANS AND CARNIVORES - IMPULSIVE NOISE

| Thresholds | Marine species and noise criteria | | |
|---|---|---|---|
| | Sirenians | Phocid carnivores (in water) | Other carnivores (in water) |
| **Noise criteria (Impulsive noise), PTS[2] onset threshold** | 190 SEL Weighted (SI) | 185 SEL Weighted (PCW) | 203 SEL Weighted (OCW) |
| | 226 Peak (Unweighted) | 218 Peak (Unweighted) | 232 Peak (Unweighted) |
| **Noise criteria (Impulsive noise), TTS[3] onset threshold** | 175 SEL Weighted (SI) | 170 SEL Weighted (PCW) | 188 SEL Weighted (OCW) |
| | 220 Peak (Unweighted) | 212 Peak (Unweighted) | 226 Peak (Unweighted) |

| | |
|---|---|
| **Behavioral** | 160 dB rms (Unweighted) |

However, the classifications have been updated in other references since the publication of the guideline. The behavioral criteria have been based on guidance provided by the Greater Atlantic Regional Fisheries Office (GARFO) [18]. The behavioral thresholds can be adjusted if background noise levels are high and are already above the prescribed values.

## 4. NOISE CRITERIA AND NOISE CONTROL

There is a range of potential impacts of anthropogenic marine noise on marine fauna species, depending on the intensity, frequency, and duration of underwater noise. The environmental values to be protected with consideration to marine noise impacts include species diversity, the ability of species to use the habitat, breed and feed without significant interferences, in accordance with the Australian Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act). In practice, this requires consideration of potential impacts of underwater noise on vulnerable and significant species within the marine ecosystem. Limiting the impact of noise to protect these environmental values is a priority during planning and performing marine projects.

Affected marine species are typically identified by the results of a biological survey of an affected area. The identified marine fauna may be broadly grouped for the purpose of establishing the underwater noise criteria. For example, an area may contain species identified as whales, sea lions, seals, dolphins, turtles and various syngnathidae fish species.

### 4.1 Reference documents

Despite the availability of results of many research programs, there are no statutory requirements and underwater noise limits in Australia. Currently, there is only one document that recommends criteria for underwater noise which was introduced by South Australia's DPTI. They have published guidelines on the acceptable exposure levels for marine fauna based on the work undertaken by Southall et al. [5] as part of the South Australian Department of Planning Transport and Infrastructure Underwater Piling Noise Guidelines [17], which are currently under review.

Other recommendations that can be used as references for establishing noise criteria include:

- Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater Acoustic Thresholds for Onset of Permanent and Temporary Threshold Shifts (NOAA Technical Memorandum NMFS-OPR-59 ,U.S. Department of Commerce, April 2018).
- Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects (Southall et al., 2019).
- Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards

Committee S3/SC1 and registered with ANSI (Popper at al., 2014).

The behavioral and physiological noise criteria for relevant species in the area of interest for impulsive noise sources (e.g., impact piling) are summarized in Tables 2 and 3. It should be noted that noise criteria in the table either correspond to criteria in the DPTI Underwater Piling Noise Guidelines [17] or stricter than the limits suggested in the document.

The general consensus is that the frequency weighting functions are applicable to the SEL, while the peak sound pressure levels should remain unweighted. The frequency weightings reflect the hearing sensitivity of mammals and are indicated by the subscript LF, HF, VHF, SI, PCW, OCW, etc. (refer to Section 3). The frequency weightings are still a subject of research and debate (i.e., for non-marine mammals), however the cumulative (24 h) unweighted SEL is considered acceptable as one of the relevant noise criteria.

In an applied construction underwater noise management context, TTS criteria are used in preference to PTS criteria to minimize the risk of irreversible auditory damage.

### 4.2 Generic noise criteria

As it was mentioned in the beginning of section 4, the project criteria should be based on the results of a biological survey of the affected area. If the results of such a survey are not available or not accurate, a more conservative approach is advisable. Section 2 describes impulsive noise criteria that are typically not weighted. If there is doubt about which marine species inhabit the affected area, the lowest noise limit for the most sensitive species in the habitat should be accepted. The available data on TTS may not cover all species that may be affected, however available references include marine fauna that require attention based on experience from many projects. Acoustic descriptors corresponding to TTS should be accepted for marine projects that involve work methods that may result in high impulsive noise exposure. One can see from the Table 3, conservative peak SPL of 196 dB can be accepted for all cetaceans to decrease risk of high noise exposure.

There are implications of using similar approaches for sound exposure level (SEL) limits. SEL of 140 dB deems to be acceptable for all the species included in Table 1 and 2. However, it should be reminded that SEL magnitudes imply implementation of weighting which is relevant to the affected species. The weighting functions vary substantially for different groups of marine fauna. The generic auditory weighting function can be presented as follows [4]:

$$W_{aud} = C + 10log_{10}\left(\frac{\left(\frac{f}{f_1}\right)^{2a}}{\left(1+\left(\frac{f}{f_1}\right)^2\right)^a\left(1+\left(\frac{f}{f_2}\right)^2\right)^b}\right), \quad (3)$$

where $f$- is the frequency within the hearing range, $f_1$ is the low frequency cut-off, $f_2$ is the high frequency cut-off, $C$- is the weighting function gain, $a$ is the low frequency exponent and $b$ is the high frequency exponent. Constants in the formula depend on the group of species under consideration and vary substantially. If the results of a bio survey are not detailed enough to identify all the species in the affected area, then most conservative weighting may be used to identify TTS zones for construction activities. For example, the auditory system of phocids is generally more sensitive to underwater noise than otariids and would give a greater estimate of exposure levels unless the dominant components of underwater noise lie within 1-5 kHz. Deriving the envelope of auditory weighting functions for a group of species to represent the most sensitive auditory function can also be considered as a way of obtaining a noise exposure estimate in the case of insufficient or unreliable information about affected species. It is recognized that the use of the envelope may overestimate the exposure from planned construction operations and require a greater buffer to be maintained. However, a precautionary approach is advisable in projects that introduce environmental risks to marine fauna.

### 4.3 Underwater noise control

There are typically two major strategies for the management of noise impacts on marine fauna during construction of marine projects that are driven by the need to protect fauna. One is the minimization of the size of the potential area in which fauna may be adversely impacted and another one is pertained to the verification that the relevant fauna are not within the potentially impacted zone.

Some recommendations on noise mitigation practices that can be found in the Underwater Piling Noise Guidelines [17] advise the following standard management and mitigation procedures with respect to piling operations:

- Avoid conducting piling activities during times when marine mammals are likely to be breeding, calving, feeding, migrating or resting in biologically important habitats located within the potential noise impact footprint
- Use low noise piling methods, instead of impact piling, where possible
- The presence of marine mammals should be visually monitored by a suitably trained crew member for at least 30 minutes before the commencement of the piling procedure
- If no marine mammals are nearby, a soft-start piling procedure should be used. This involves gradually increasing the piling impact energy over a 10-minute time period. Visual observations of marine mammals within the exclusion zone should be maintained by trained crew throughout the start period
- If a marine mammal is sighted within the observation zone during the soft start of normal operation procedures, the operator of the piling rig should be placed on stand-by to shut down the piling rig.

Other noise reduction options can also be used to reduce noise from piling and other noise intensive activities. These include pile head cushion blocks, bubble curtains and aerated, damped or dewatered outer pile casings. A cushion block is made of an energy absorbing material such as wood or nylon to reduce the generation of high frequency vibrations in the pile during pile impact. Marine noise reductions of 11-26 dB are reported for wood blocks and 4-5 dB for nylon blocks applied to 300 mm hollow steel piles [19]. A bubble curtain consists of a series of vertical-spaced air diffuser rings on a frame that is lowered around the pile. The change in effective water density created by the curtain of air bubbles around the pile reduces the sound transmission to the surrounding water. This method is not recommended for open waters subject to cross currents. In these conditions, reported results show unreliable attenuation.

A dewatered or aerated isolation casing system uses a concentric outer shell around the driven pile to contain either a complete air gap or an aerated bubble layer. In situations subject to tidal flows, isolation casing attenuation is more reliable than an unconstrained bubble layer, which may have the continuity of the bubble layer degraded by cross currents. This method does however require significant alteration to the pile installation methodology. Attenuations up to 15 dB have been demonstrated for the aerated option and over 20 dB for the dewatered option in some case studies.

The use of a damped outer casing has been demonstrated for steel casings 760 mm and 910 mm in diameter. The use of outer damping layers as an attenuation method offers greater reliability than aerated or dewatered casing systems.

A summary of the effectiveness of alternative attenuation methods is reproduced in Table 3 based on data collected by both California and Washington State Departments of Transportation [19].

**TABLE 3:** THE MATERIAL PROPERTIES OF THE STRUCTURE.

| Attenuation method | SEL Attenuation | Pile diameter |
|---|---|---|
| Plywood pile cushion | >11 dB | No known data demonstrating effectiveness on steel piles greater than 300 mm diameter |
| Aerated shell casing | >10 dB<br>>18 dB | 0.76 m diameter steel pile<br>2.4 m diameter steel pile |
| Dewatered shell casing | >20 dB<br>>12 dB | 2.4 m diameter steel pile<br>0.91 m diameter steel shell |
| Damped shell casing | >15 dB<br>>8 dB | 0.91 m diameter steel shell around pile with 50 mm closed cell internal lining<br>0.76 m diameter hollow steel ‘thermos’ shell around pile, with 50 mm dry mineral wool fiber in cavity. |

To mitigate the risk of excessive impact on marine fauna, an appropriate combination of noise mitigation strategies could be adopted as part of reasonable and practicable measures. It is noted that noise mitigation strategies should only be implemented in a way when they do not cause significant modification of the work method, delay or extend the duration of piling operations. Otherwise, it may increase the risk that marine fauna is exposed to high levels of noise from impact piling for a longer period.

Each of the mitigation strategies included in Table 4 provides several measures to reduce the likelihood of the occurrence of adverse effects from impact piling. Where marine species are likely to be present during piling operations, strategies which facilitate the identification of the marine fauna should allow for operations to be modified or stopped to minimize the likelihood of unacceptable exposure to noise levels. The risk of impact piling resulting in adverse effects to cetaceans and all other relevant species may be considered low if an appropriate combination of noise mitigation strategies is implemented during the piling stage of the project.

**TABLE 4:** THE MATERIAL PROPERTIES OF THE STRUCTURE.

| Type | Attenuation method | Pile diameter |
|---|---|---|
| Operational measures | Alternative piling method | Utilise low noise impact techniques such as suction piling or vibro- piling in preference to impact piling where possible. |
| | Soft start procedure at the start of piling | Impact energy to be gradually increased at the commencement of piling over a 3-5 minute period, with noise levels to gradually increase to their maximum values. Soft start procedure should be implemented at the commencement of piling each time, if piling is stopped for a period longer than 3 hours, or if piling is stopped due to marine mammals or turtles entering the impact zone where the TTS criterion is exceeded. |
| | Design of construction program to minimise impulsive noise | Impact piling should be scheduled to occur for the minimum practical total duration, to reduce the likelihood that endangered species will be exposed to piling noise.<br>Impact piling should not be scheduled during night time periods when marine mammals will be difficult to observe. This is also the time of day when turtle movements are more likely to occur.<br>Piling should be scheduled outside of the months when cetaceans may be present in the area of works. |
| Observation | Safety zones | Observation and shut-down zones around work zones should be identified in accordance with the results of noise impact predictions. In the observation zone, the movement of marine species should be monitored to determine whether they are moving towards or entering the shut-down zone. When a marine species is sighted |

| | | |
|---|---|---|
| | | within or may enter the shut-down zone, pile driving must be stopped as soon as possible. Safety zone dimensions are based upon the radial distance from the noise source. The extent of the safety zones should be based on the size of the predicted zones of non-acceptable noise impact (300 m for shut-down zone is suggested based on noise predictions), but also need to account for practicality of monitoring for the presence of marine fauna. A shutdown zone of greater than 1 km may be difficult to monitor. Observation zones should be as large as practicable. |
| | Marine Mammal Observer (MMO) | A trained MMO should be engaged to monitor safety zones prior to and during all pile driving activities. |

## 5. CONCLUSION

This paper reviews approaches for establishing noise limits to limit noise impact from marine projects. Hearing sensitivities and relevant physiological and behavioural noise criteria for species that may be affected during the construction of marine projects were developed based on a review of available scientific research. This review also highlights the need for more insight into approaches that can be used for establishing underwater noise limits to limit the impact from anthropogenic activities on marine fauna.

General approaches to mitigate the noise from construction of offshore projects are also considered in this paper. An emphasis needs to be placed on thorough planning of construction operations prior to execution of marine projects, which should incorporate managerial and technological measures to minimise impact on marine fauna.

## REFERENCES

[1] Jensen Finn B., Kuperman William A., Porter Michael B., and Schmidt Henrik. *Computational Ocean Acoustics*, Springer-Verlag, New York (2000).

[2] Wenz, Gordon .M. “Acoustic ambient noise in the ocean: Spectra and sources.” The Journal of the Acoustical Society of America, Vol. 34, 1936 No.12 (1962): pp. 1936-1956.

[3] Mellen, Robert H. “ Thermal noise limit in the detection of underwater acoustic signals.” Journal of Acoustical Society of America, Vol. 24 No.5 (1952): pp. 478-480.

[4] National Marine Fisheries Service. “Revisions to: Technical guidance for assessing the effects of anthropogenic sound on marine mammal hearing (version 2.0): Underwater thresholds for onset of permanent and temporary threshold shifts.” U.S. Department of Commerce, NOAA Technical Memorandum NMFS-OPR-59.2018.

[5] Southall, Brandon L., Bowles, Ann E., Ellison, William T., Finneran James J., Gentry Roger L., Green Charles R., Kastak David, Ketten Darlene R., Miller James H., Nactigall, Paul E., Richardson, W. John, Thomas, Jeanette A., and Tyack Peter L. “ Marine Mammal Noise Exposure Criteria, Aquatic Mammals.” Vol. 33 No.4 (2007): pp.411-509.

[6] Southall, Brandon L., Finneran, James J., Reichmuth, Coleen, Nachtigall, Paul E., Ketten, Darlene R., Bowles, Ann E., Ellison, William T., Nowacek, Duglas P. and Tyack, Peter L. “Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects.” Aquatic Mammals, Vol. 45 No.2 (2019) pp. 125-232.

[7] Hawkins, Anthony D. and Popper, Arthur N. “Effects of noise on fish, fisheries and invertebrates in the U.S. Atlantic and Arctic from energy industry sound-generating activities: A literature synthesis.” The U.S. Department of the Interior Bureau of Ocean Energy Management Contract M11PC00031. 2012.

[8] Popper, Arthur N., Hawkins, Anthony D., Fay, Richard R., Mann, David A., Bartol, Soraya, Carlson, Thomas J., Coombs, Sheryl, Ellison, William T., Gentry, Roger L., Halvorsen, Michelle B., Lokkeborg, Svein, Rogers, Peter H., Southall, Brandon L., Zeddies, David G. and Tavolga, William N. “Sound exposure guidelines for fishes and sea turtles.” A technical report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI, ASA Press Springer.2014.

[9] Ketten, Darlene R. and Bartol Soraya M. “Functional Measures of Sea Turtle Hearing –Final Report.” Woods Hole Oceanographic Institution, Woods Hole, MA. 2005.

[10] Ketten, Darlene R. “Underwater ears and the physiology of impacts: Comparative Liability for Hearing Loss.” Sea Turtles, Birds and Mammals, Bioacoustics, Vol. 17 No.103 (2008): pp. 315-318.

[11] Martin, Kelly J., Alessi, Sarah C., Gaspard, Joseph C., Tucker, Anton D., Bauer, Gordon B. and Mann, David A. “Underwater hearing in the loggerhead turtle (Caretta caretta): a comparison of behavioural and auditory evoked potential audiograms.” Journal of Experimental Biology 215 (2012): pp. 3001-3005.

[12] Dooling, Robert .J. and Therrien, Sara C. “Hearing in birds: What changes from air to water.” *The Effects of Noise on Aquatic Life*, Advances in Experimental Medicine and Biology 730 (2012): pp.77-82.

[13] Johansen, S., Larsen, O.N., Christensen-Dalsgaard, J., Seidelin, L., Huulvej, T., Jensen, K., Lunneryd, S., Bostrom, M. and Wahlberg, M. “ In-air and underwater hearing in the great cormorant (Phalacrocorax carbo sinensis).” *The Effects of Noise on Aquatic Life*, Advances in Experimental Medicine and Biology 875 (2016): pp.505-521.

[14] Salgado Kent, Chandra P. and McCauley, Robert D. “ Preliminary report and summary of work to Dec 2006 to ascertain if hearing damage has occurred in wild gold band snapper due to seismic survey exposure.” Centre for Marine Science, MST Report No 2006-54, Curtin University. 2006.

 

[15] Weilgart, Linda. “The impact of ocean noise pollution on fish and invertebrates.” Report, Dalhousie University, OceanCare. 2018.

[16] GHD Pty Ltd. “Port of Townsville Limited Report for Berth 12 Underwater Noise Assessment.” GHD. 2011.

[17] Department of Planning, Transport and Infrastructure. “Underwater piling noise guidelines”. Government of South Australia. 2012.

[18] Greater Atlantic Regional Fisheries Office. Consultation Technical Guidance in the Greater Atlantic Region.2022.Available: http://www.greateratlantic.fisheries.noaa.gov/protected/section7/guidance/consultation/index.html

[19] ICF Jones & Stokes and Illingworth & Rodkin Inc. “Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish.” Final report to the California Department of Transportation. 2009.