



# Effects of Concurrent Pile Driving on Marine Mammal Acoustic Range


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## Abstract

Underwater sound levels during offshore wind foundation installation may have significant behavioral and physiological impacts on marine mammals. The rapid growth of offshore wind development has led to the need for further acceleration of construction schedules by means of simultaneous installation of multiple foundations. While offshore wind development projects in the USA are proposing the concurrent pile-driving approach as part of the overall construction schedule, the resultant underwater acoustic impacts on marine mammals have not yet been thoroughly analyzed. In this chapter, the effects on the underwater sound field due to the concurrent installation of a monopile with a jacketed pin pile using an impact hammer at various separation distances are assessed. In addition, acoustic

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ranges to the relevant regulatory thresholds for auditory injury (AUD INJ) and behavioral disturbance of marine mammals are presented and compared to ranges from traditional single pile installation.

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**Keywords**

Underwater acoustics · Offshore wind · Pile installation · Simultaneous activities · Acoustic modeling · Marine species · Auditory injury · Behavioral disturbance

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**Introduction**

As offshore wind energy rapidly expands to meet growing demands for renewable power, the pace and scale of construction have intensified—often proposing simultaneous installation of multiple foundations. Based on research of public data, concurrent pile driving has not been used to construct any commercial offshore wind farms; however, it is proposed for various developments in Europe and the USA, including the Berwick and Muir Mhòr Wind Farms in Scotland and the Sunrise Wind Farm in the USA. While this concurrent pile-driving approach offers logistical and economic advantages, it raises critical concerns about its acoustic footprint in marine environments. Marine mammals, which are highly sensitive to anthropogenic sound, may experience a range of adverse effects, from behavioral disruptions to auditory injuries. However, the cumulative acoustic impacts of concurrent foundation installations remain insufficiently understood, particularly in US waters where such practices are increasingly proposed. This study investigates the underwater sound fields generated by the concurrent installation of monopiles and jacketed pin piles at varying separation distances. To date, regulatory guidance on concurrent pile driving has been limited, and a few studies have evaluated its directional effects on acoustic propagation and ranges. By evaluating acoustic propagation and comparing ranges to regulatory thresholds for auditory injury (AUD INJ) and behavioral disturbance, this study aims to illuminate the potential risks to marine mammals and inform effective mitigation strategies for sustainable offshore wind development.

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**Concurrent Pile-Driving Scenario Development**

Concurrent pile driving in offshore wind construction involves installing multiple turbine foundations simultaneously. However, owing to the limited number of vessels capable of installing large monopiles, concurrent installation is generally restricted to a combination of a monopile and a pin pile. To develop a scenario representative of the installation of offshore wind farms in the USA, a review of recent Construction and Operation Plan (COP) applications was completed. This review determined that monopile diameters ranged from 9 m to 16 m, and pin pile

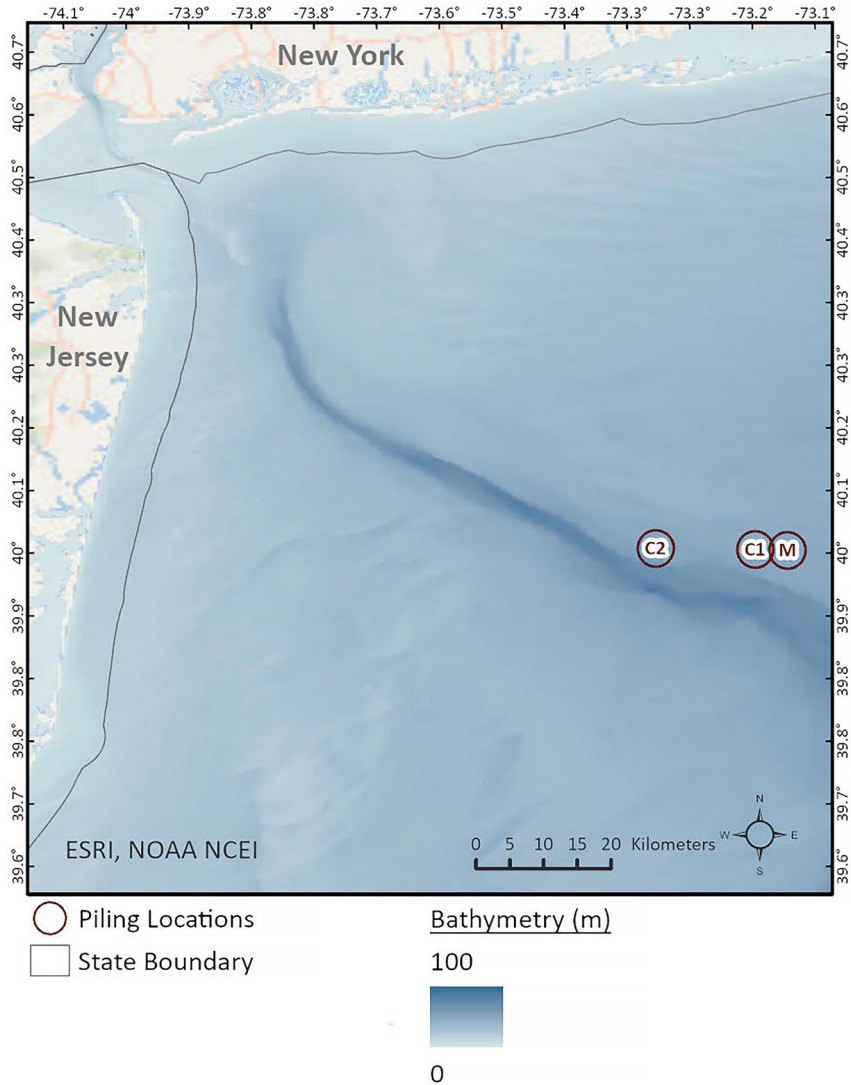
diameters ranged from 2.5 m to 5 m. The installation of monopiles and pin piles involves implementing different pile progressions (i.e., sequences of hammer energy and strikes) due to site-specific sediment variability. To develop a representative scenario for this study, the median of the pile diameters was selected. The pile progressions for the monopile and pin pile were averaged from the data provided in the COP applications for piles of the same diameter. The monopile and pin pile progressions included in this analysis are provided in Table 1.

To evaluate the effects of concurrent piling at different distances, a central monopile location (M) was selected based on the total Euclidean distances from proposed offshore wind development areas along the US East Coast. To prevent overlap with existing or ongoing wind projects, location M was placed away from these areas. In addition to location M, two pin pile locations were also selected. The first pin pile location (C1) was situated two nautical miles (nm) from the monopile. The separation distance of 2 nm was chosen as it is consistent with separation distances assumed in COP applications and is cited as the minimum distance at which two installation vessels can safely operate. The second pin pile location (C2) was positioned 15 nm from the monopile. Figure 1 shows the modeling locations.

By including a 15 nm separation distance for C2, the study effectively samples two extreme points in the lease area: one that tests the feasibility of closely spaced activities and another that reflects data from a significantly larger, more separated part of the potential site. Isoleths for HF and VHF AUD INJ occur generally closer to the pile; therefore, the 2 nm separation distance and certainly the 15 nm separation distance make simultaneous auditory injury from two separate sites improbable. Conversely, LF AUD INJ and behavioral disturbance zones can be extensive, sometimes extending up to 8 km or even 10 km away from the source for a single pile installation, depending on the hammer energy, mitigation measures, oceanographic conditions, and marine mammal species. The 2 nm separation distance is well within the potential ranges for LF AUD INJ and behavioral disturbance of both piles. The 15 nm separation distance may also result in

**Table 1** Impact pile-driving schedule for concurrent foundation installation

Pile diameter (m)	Hammer energy (kJ)	Strike rate (strikes/min)	Total number of strikes	Total duration (min)
12	880	40	1543	220
	2200	40	2656	
	3080	40	2114	
	4400	40	2469	
4.25	1050	40	3017	301
	1750	40	1667	
	2450	43	2333	
	3500	38	4800	



**Fig. 1** Modeled pile locations for the main location (M), concurrent location with 2 nm separation distance (C1), and concurrent location with 15 nm separation distance (C2)

cumulative exposure for certain species. This means that a marine mammal could realistically be exposed to sound levels from both sites simultaneously, experiencing overlapping sound exposure.

## Impact Pile-Driving Parameters

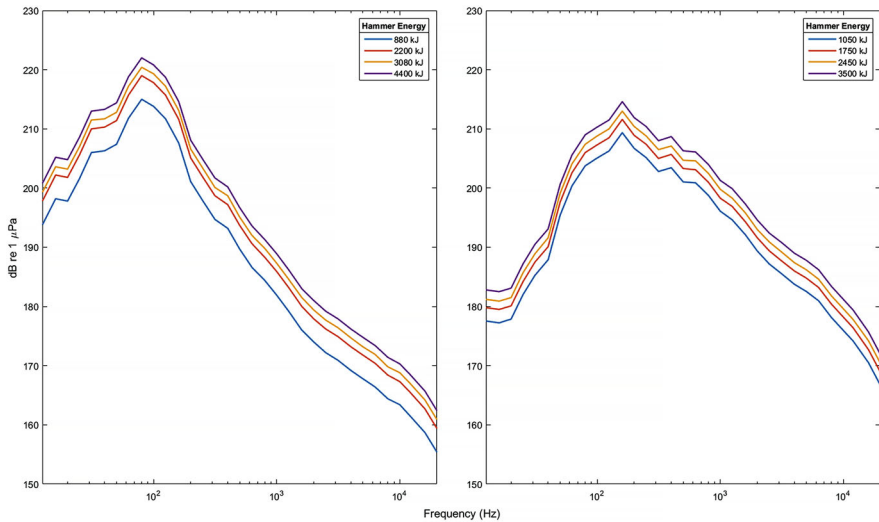
### Source Characterization

Tetra Tech has developed a robust empirical modeling approach to estimate underwater sound source levels for impact pile driving, using data from various pile diameters, hammer energies, and measurement distances. This method involves normalizing sound pressure levels for transmission loss, adjusting for site-specific hammer energy, and applying regression analysis to relate sound levels to pile diameter. Spectral data for monopiles and pin piles are also normalized to ensure consistent energy representation across pile sizes, with averaged spectral shapes used to characterize acoustic output. The source levels used in this analysis are provided in Table 2, presented in terms of sound exposure level (SEL) and sound pressure level (SPL). Figure 2 shows the sound source spectra for the monopile and pin piles in terms of SEL.

The dominant factor influencing underwater noise from impact pile driving is hammer energy, while soil type and resistance appear to have minimal correlation with measured sound levels. The modeling framework employed here enables

**Table 2** Pile-driving sound source level

Pile diameter (m)	Maximum hammer energy (kJ)	SEL (dB re 1 $\mu\text{Pa}^2\text{-s}$ )	SPL (dB re 1 $\mu\text{Pa}$ )
12	4400	227	238
4.25	3500	221	231



**Fig. 2** The 12 m monopile (left) and 4.25 m pin pile (right) sound source spectra, as derived from the empirical model

accurate predictions of acoustic impacts and supports the development of effective mitigation strategies to limit the impacts on marine mammals during offshore wind development. A comparison of published sound field verification (SFV) measurement data with Tetra Tech's empirical model confirmed the model's reliability. The analysis revealed that the published SFV data—collected at 750 m from pile-driving activities—and the model's predicted sound source level at 750 m had a maximum difference of only 3 dB. This close alignment with SFV measurements demonstrates the model's accuracy. Furthermore, by basing this comparison on the highest measured values for each metric, the model is confirmed to have a conservative, yet effective, ability to predict sound source levels. Additional validation using confidential data from a US offshore wind farm further supported the model's effectiveness in estimating sound propagation during impact pile driving. Notably, the modeled values consistently exceeded measured values, underscoring the model's conservative approach—an important factor in environmental assessments for marine species.

## Impact Pile Driving Propagation Modeling

To evaluate the sound propagation at the specified piling locations, a sound propagation model utilizing a parabolic equation (PE) model for low frequencies (12–800 Hz) and a ray-tracing model for high frequencies (1–20 kHz) was used. The models incorporated key environmental parameters, including site-specific bathymetry, sound speed profiles (SSP), and sediment layers.

Bathymetry data were obtained from the US Coastal Relief Model (NOAA National Centers for Environmental Information 2023), which provides a horizontal resolution of 1 arc-second (~31 m) and was projected to UTM Zone 18 N. The bathymetry extents for the foundation installations covered an area of 100 km by 100 km, with a maximum depth of 87 m.

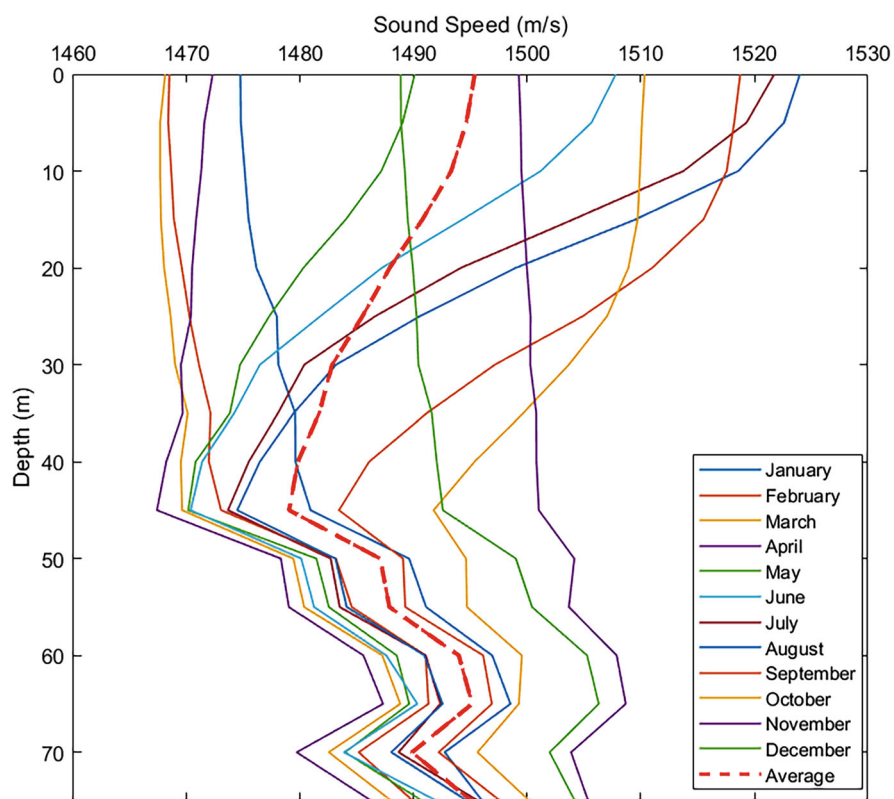
Seafloor properties were obtained from publicly available geophysical and geo-technical databases. Due to the insufficient data on sediment properties at greater depths in the study area, sediment layers were estimated by assuming a power law relationship with depth, reflecting changes in porosity with increasing overburden weight (Ainslie 2010; Hamilton 1980). The sediment parameters used in this study are summarized in Table 3.

The SSP was obtained from the World Ocean Atlas 2018 dataset using the Sound Speed Manager (Masetti et al. 2017). The monthly SSP from May through December reflects the typical construction period of offshore wind projects along the US East Coast. The average SSP for this period was selected for this study and is shown in Fig. 3.

The cumulative SEL for the pile-driving sound source was modeled as a vertical line source, taking into account the speed of sound in steel for the pile. The line source uses a vertical array of point sources spaced 1 m apart. Using the single strike SEL ( $L_{E,1 \text{ strike}}$ ) obtained from the empirical model, the cumulative SEL of the sound

**Table 3** Modeled sediment and associated geoacoustic properties

Sediment type	Depth	Compressional sound speed (m/s)	Density (kg/m <sup>3</sup> )	Attenuation (dB/λ)
Coarse sand	0	1650	1900	0.87
	10	1712	1971	
	20	1752	2017	
	30	1762	2029	
	40	1772	2040	
	50	1782	2051	
	60	1787	2057	
	70	1792	2063	
	80	1797	2069	
	90	1802	2074	
	100	1807	2080	

**Fig. 3** Sound speed profile used in the modeling

source is calculated using the following equation to distribute the sound emissions across the vertical array, for a specified number of strikes ( $N$ ):

$$L_{E,N} = L_{E,1 \text{ strike}} + 10 \log_{10}(N) \quad (1)$$

The SPL calculation is set up identically to the SEL calculation, with one key difference: for SPL, the total number of anticipated pile-driving strikes within the 24-hour assessment period is not incorporated. Instead, SPL calculations evaluate the sound level produced by a single pile-driving strike at the maximum hammer energy.

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## Regulatory Acoustic Thresholds

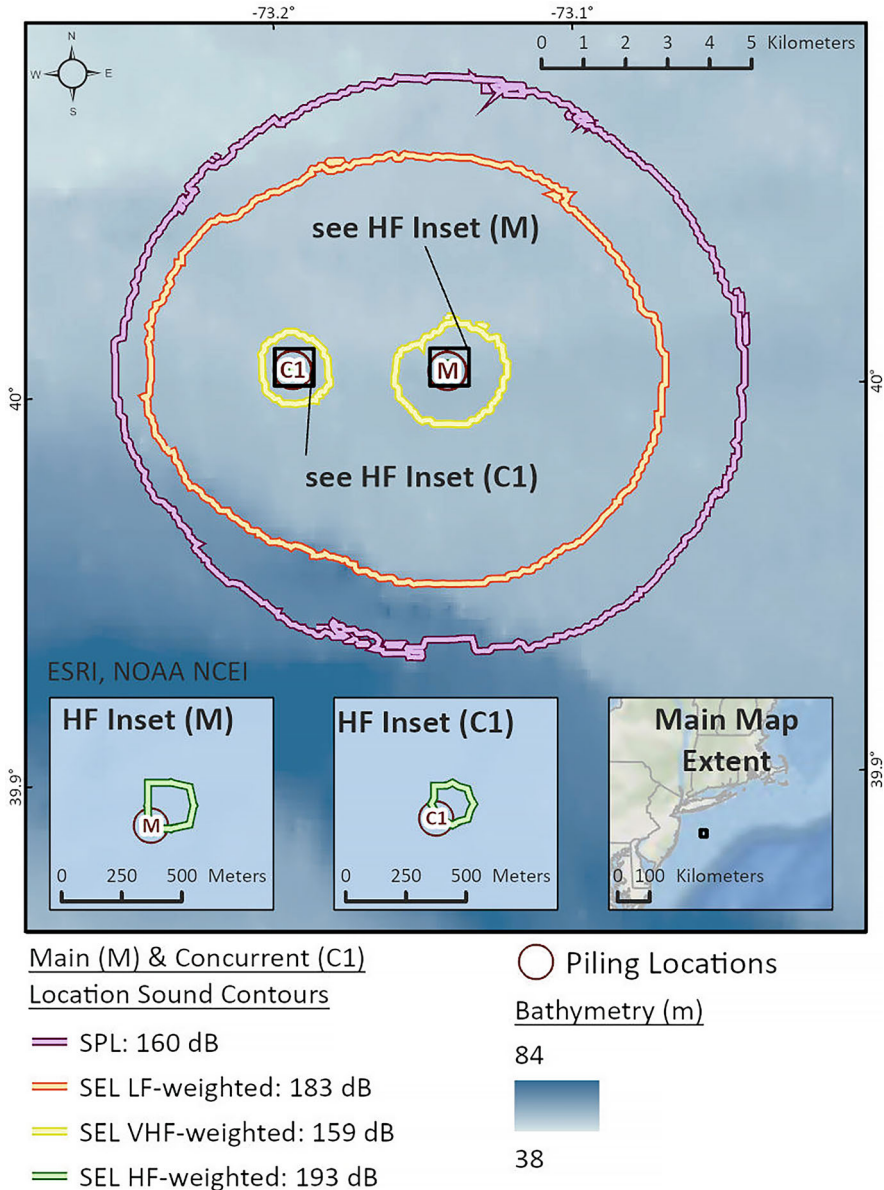
To evaluate the influence of concurrent pile driving on sound propagation and its potential impacts on marine mammals, this analysis uses the acoustic thresholds for auditory injury (AUD INJ/Level A) and Behavioral Disturbance (Level B) for marine mammals as defined by NOAA Fisheries' Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (2024). These thresholds serve as the basis for all underwater acoustic assessments of offshore wind farms in the USA and provide a direct reference for regulators to assess the effects of pile driving.

The AUD INJ threshold incorporates hearing group-specific weightings and is based on the cumulative sound exposure level ( $L_{E,p,24h}$ ) over a 24-hour accumulation period. In this study, low-frequency (LF) cetaceans, high-frequency (HF) cetaceans, very high-frequency (VHF) cetaceans, and phocid pinnipeds in water (PW) were evaluated. Otariid pinnipeds in water (OW) were excluded due to their absence from the US East Coast. The Behavioral Disturbance threshold is defined as a root-mean-squared (RMS) sound pressure level ( $L_{p,rms}$ ) of 160 dB for impulsive sounds, based on the unweighted instantaneous sound level of a single hammer strike. For the purposes of this study, it is assumed that both piles in concurrent pile-driving scenarios are struck simultaneously, consistent with the instantaneous nature of the Behavioral Disturbance threshold.

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## Results

Underwater sound propagation modeling was first conducted for the main location (M), with distances calculated to both the AUD INJ and Behavioral Disturbance thresholds. To evaluate the effects of concurrent operations, additional scenarios were modeled in which a pin pile was installed 2 nm west of the monopile (C1, shown in Fig. 4) and 15 nm west of the monopile (C2, shown in Fig. 7). For each concurrent scenario, the sound fields from the monopile and pin pile installations were logarithmically combined to represent the cumulative acoustic environment.



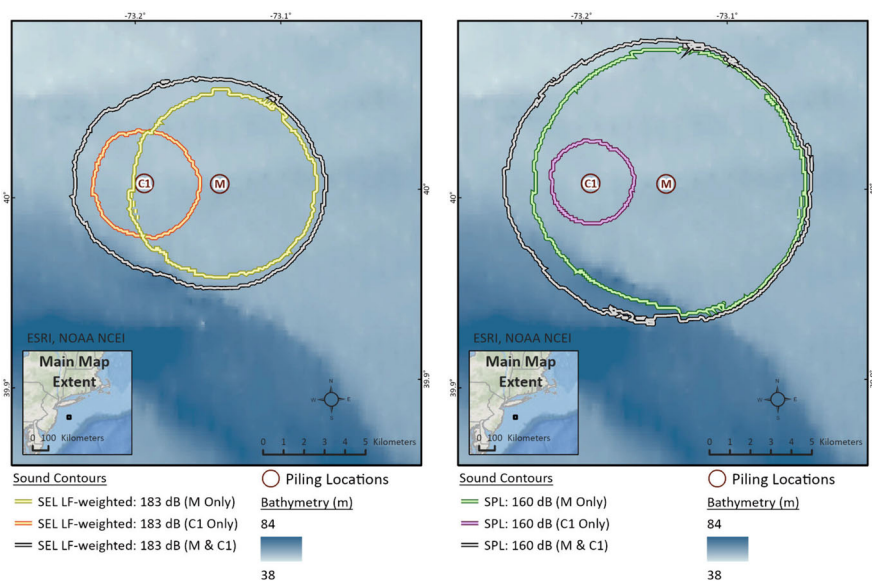
**Fig. 4** Combined sound contours for concurrent pile driving at M and C1 locations

As shown in Fig. 4, when concurrent pile driving occurs with a 2 nm separation, the cumulative contours for the HF and VHF AUD INJ thresholds show little expansion, indicating minimal additive effects for those hearing groups. However, the LF AUD INJ and Behavioral Disturbance thresholds result in combined contours

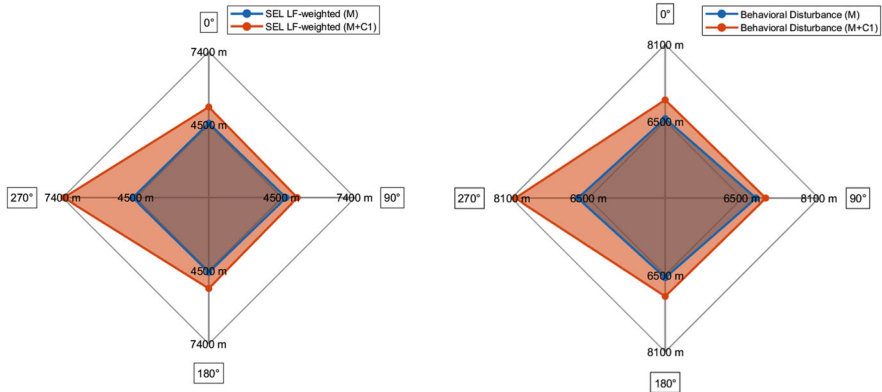
that have increased received levels in the overlap zones as well as expanded acoustic ranges, reflecting the combined energy from the union of both sources (Fig. 5). For LF AUD INJ, there is substantial overlap between the sound fields of the M and C1 locations and which may result in greater risk for AUD INJ due to higher received levels in the intersection of the two sound fields. For Behavioral Disturbance, the combined field is largely dominated by the larger pile: it effectively engulfs the C1 sound field while extending the overall disturbance footprint.

A comparative analysis demonstrates the increase in acoustic ranges between a single monopile installation and the concurrent scenario with a pin pile 2 nm to the west (Fig. 6). The greatest influence of concurrent operations is observed in the direction of the pin pile ( $270^\circ$ ). For LF cetaceans, the concurrent scenario increases the AUD INJ distance by 2740 m to the west, 643 m to the north and south, and 450 m to the east, representing a maximum overall increase of approximately 59%. For Behavioral Disturbance, the concurrent scenario increases the distance by 1300 m to the west, 391 m to the north and south, and 203 m to the east, resulting in a maximum overall increase of approximately 19%. The influence on HF, VHF, and PW AUD INJ distances is minimal, with changes of 15 m or less. These results highlight that the cumulative acoustic impact of concurrent pile driving is most pronounced for LF AUD INJ and Behavioral Disturbance, particularly in the direction of the additional pile, while effects on other hearing groups are relatively minor.

When the concurrent operations are moved farther from the monopile, a similar trend is observed, but the influence on acoustic propagation is significantly reduced. The combined sound field from the monopile and pin pile installations at a



**Fig. 5** Sound contours for concurrent pile driving at M and C1 locations presented individually for SEL LF (left) and SPL unweighted (right) metrics

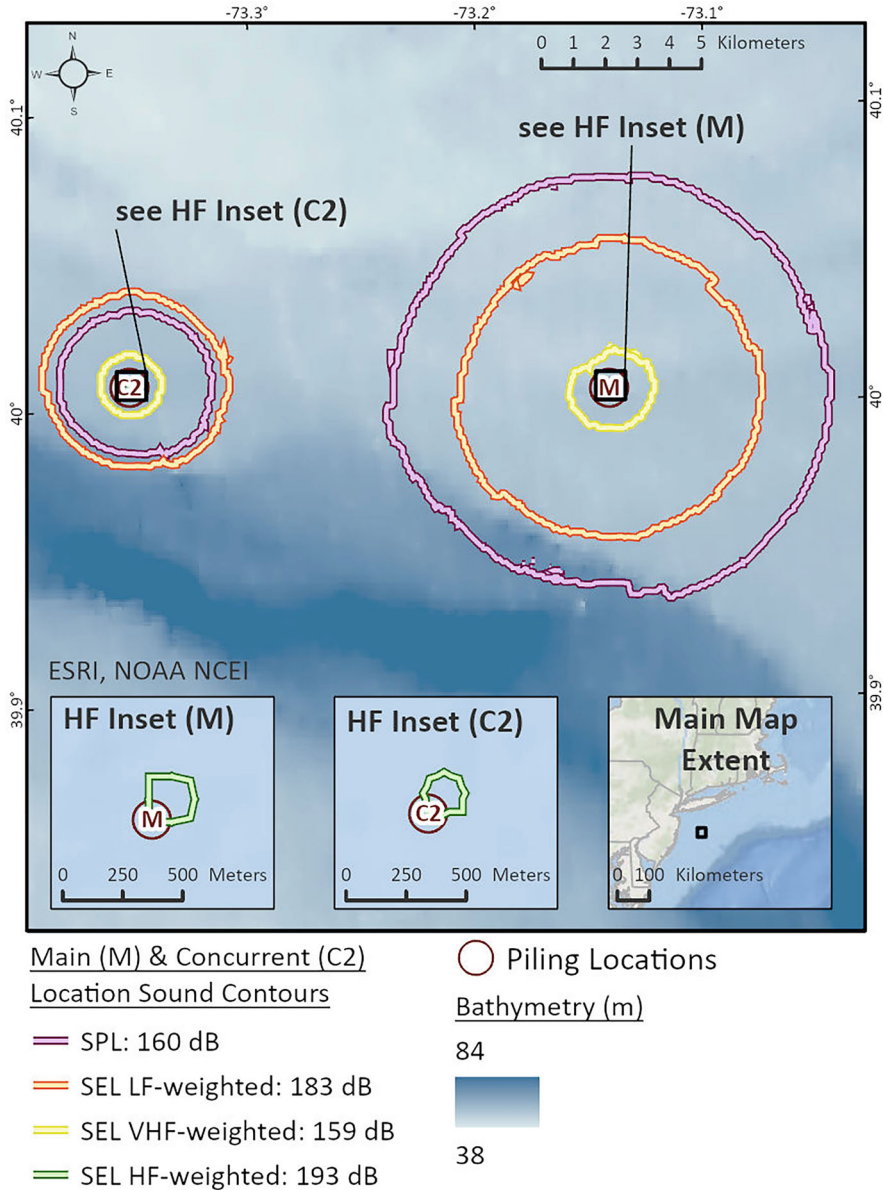


**Fig. 6** Radar plots showing changes to acoustic range for LF AUD INJ and Behavioral Disturbance thresholds for concurrent pile driving at M and C1 locations. Please note the difference in axes limits

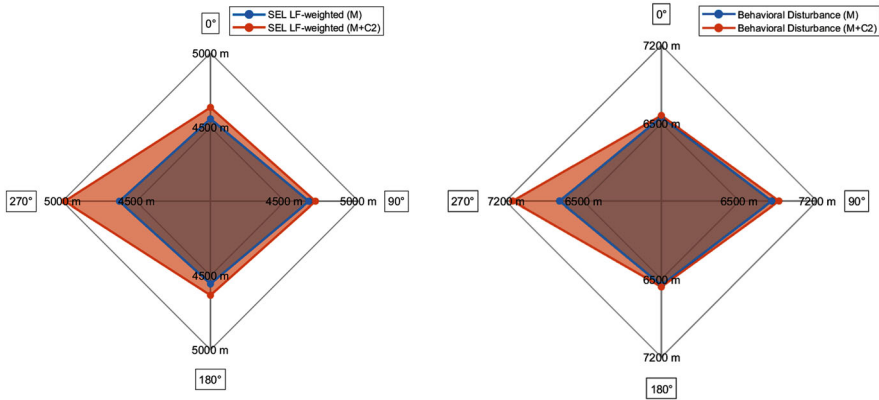
separation distance of 15 nm produces a contour that clearly delineates two distinct sources, as shown in Fig. 7.

In this scenario (Fig. 8), the concurrent installation increases the LF AUD INJ distance by 370 m to the west, 77 m to the north and south, and 45 m to the east, resulting in a maximum overall increase of approximately 8%. For Behavioral Disturbance, concurrent operations at 15 nm increase the distances by 422 m west, 15 m north and south, and 66 m east, corresponding to a maximum overall increase of approximately 6%. These results demonstrate that as the separation distance between concurrent piles increases, the cumulative acoustic impact diminishes and the sound field becomes more spatially separate, essentially functioning as two distinct activities.

In terms of animal exposure, when sound fields are distinct, different subsets of the population may be exposed to single-pile levels. When piling activities are close together and sound fields overlap, an individual may be exposed to impulses from multiple sources, causing sound energy to accumulate quickly within the animal’s auditory system. This rapid accumulation leads to a higher total cumulative energy level and increases the likelihood of temporary or permanent hearing loss over time. Conversely, sufficient distance between piles attenuates the sound intensity from distant sources, slowing the rate of cumulative energy buildup and lowering the overall accumulated energy. Increased separation distance thus acts as a buffer, minimizing the potential for summed acoustic impacts to individuals, while increasing the geographic area over which single-pile impacts may occur. Although the regulatory threshold contours are spatially separate, an individual in the intersection of the two sound fields may still experience behavioral effects and/or masking. Exposure impacts due to concurrent pile driving are analyzed in detail in ► [“Estimating the Acoustic Exposure of Marine Mammals and Sequential Pile Driving”](#).



**Fig. 7** Combined sound contours for concurrent pile driving at M and C2 locations



**Fig. 8** Radar plots showing changes to acoustic range for LF AUD INJ and Behavioral Disturbance thresholds for concurrent pile driving at M and C2 locations. Please note the difference in axes limits

## Conclusions

Concurrent operation of impact hammers for both monopile and pin pile installations results in increased threshold distances for the AUD INJ threshold for LF cetaceans and the Level B/Behavioral Disturbance threshold. The greatest increases in distance occur in the direction of the pin pile, but elevated threshold distances are observed in all directions from the monopile. Specifically, when evaluating the separation distance of 2 nm, the LF AUD INJ threshold distance increases by up to 2700 m, and the Behavioral Disturbance threshold increases by up to 1300 m, corresponding to overall increases of 59% and 19% in the respective acoustic ranges. Therefore, even though it was considered unlikely that distances to AUD INJ thresholds would be influenced by concurrent pile driving, that was not what the results of this study showed. These increases may have important implications for noise mitigation and monitoring strategies during foundation installation.

As the separation distance between concurrent operations increases, the influence on threshold distances diminishes; however, even at a separation distance of 15 nm, there is still a 370-m increase in the LF AUD INJ threshold and a 422-m increase in the Behavioral Disturbance distance, representing 8% and 6% increases, respectively. If the effects of concurrent piling are not considered—even with substantial separation distances—abbreviated sound field verification (ASFV) may indicate threshold exceedances, potentially triggering additional mitigation requirements.

The propagation modeling results for concurrent piling are sensitive to various factors, including pile diameter, hammer energy, bathymetry, sediment properties, and sound speed. As shown in this study, concurrent operations can present challenges, including the need for expanded monitoring zones and accurately evaluating compliance with ASFV requirements. However, the overall increases in threshold

distances are within a manageable range and can be addressed through mitigation. Importantly, concurrent pile installation accelerates offshore wind farm construction, reducing the overall duration and cumulative sound exposure in the marine environment. With appropriate mitigation, this may ultimately reduce long-term exposure risks for marine mammals.

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## Cross-References

- ▶ [Estimating the Acoustic Exposure of Marine Mammals Due to Concurrent and Sequential Pile Driving](#)

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

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