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Cite as: JASA Express Lett. **2**, 071201 (2022); https://doi.org/10.1121/10.0012348
Submitted: 01 March 2022 • Accepted: 13 June 2022 • Published Online: 01 July 2022

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JASA EXPRESS LETTERS ARTICLE asa.scitation.org/journal/jel

Kurtosis analysis of sounds from down-the-hole pile installation and the implications for marine mammal auditory impairment

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Abstract: Sounds from down-the-hole pile installation contain both impulsive and non-impulsive components. Kurtosis values (β) were determined for two datasets to investigate the impulsiveness of piling sounds. When the hammer struck the pile(s), β was 21–30 at 10 m and approximately 10 at 200 m. When the hammer was used for drilling without contacting the pile, β was 4–6 at all distances. These findings suggest that a simple dichotomy of classifying sounds as impulsive or non-impulsive may be overly simplistic for assessing marine mammal auditory impacts and studies investigating the impacts from complex sound fields are needed.

[Editor: Wu-Jung Lee] https://doi.org/10.1121/10.0012348

Received: 1 March 2022 **Accepted:** 13 June 2022 **Published Online:** 1 July 2022

1. Introduction

To assess impacts of anthropogenic underwater sounds on marine mammals, action proponents and regulators are required to determine whether the sound of interest is impulsive or non-impulsive, as the regulatory acoustic thresholds differ for those two categories of sources (NMFS, 2018). The regulatory community generally has categorized sound sources as either impulsive (e.g., impact pile driving and seismic airgun) or non-impulsive (e.g., vibratory pile driving, drilling, and shipping) (Guan *et al.*, 2021).

However, this dichotomy of sound source classification may be overly simplistic. For example, sound generated from down-the-hole (DTH) pile installation, a relatively new piling technology that uses a hammer to advance a pile into the sediment or to drill a hole to reinforce a pile by percussive drilling while pumping and airlifting cuttings and debris, generates complex sounds that include both impulsive and non-impulsive components (Guan and Miner, 2020; Reyff, 2020; Guan *et al.*, 2022). As proposed by Harris (1998) and adopted by Southall *et al.* (2007), a difference of 3 dB between a 1 s averaged root mean square sound pressure level ($L_{p,rms}$) and a 35 ms averaged $L_{p,rms}$ of the signal is commonly used to differentiate impulsive and non-impulsive sounds. If the $L_{p,rms}$ of the 35 ms average is at least 3 dB greater than that of the 1 s average, then the signal is classified as impulsive; otherwise, it is considered non-impulsive.

As an example, when using the Harris (1998) method to analyze sound characteristics from DTH pile installation from two dock construction projects in southeastern Alaska, the types of sound generated were dependent upon how the DTH hammer was operating (Guan and Miner, 2020; Guan *et al.*, 2022). When the DTH hammer directly struck the steel pile shoe during percussive drilling, the difference between the 35 ms and 1 s averaged $L_{p,rms}$ was 3.4 dB, and the sound was considered impulsive (Guan and Miner, 2020). But when the hammer was used to conduct percussive drilling without contacting the pile, the difference was only 2.0 dB, and the sound could have been considered non-impulsive (Guan *et al.*, 2022). Based on these results, it was suggested that DTH pile installation be separated into two categories: (1) DTH pile driving with the hammer striking the pile shoe and (2) DTH pile drilling with no contact between hammer and the pile.

The Harris (1998) method can be difficult to implement and can be subjective, as time-gating of the signals for comparison is a tedious and sensitive process when the signal-to-noise ratio is low due to reverberation within a very short inter-pulse interval (e.g., sounds emitted during DTH pile installation). DTH pile driving and DTH pile drilling also typically occur at a rate of more than 10 strikes per second (Reyff, 2020; Guan *et al.*, 2022). Similar to impact pile driving, a 1 s averaged $L_{p,rms}$ represents a collection of many pulses within that duration.

Recently, a more objective approach of using kurtosis, which is a measure of the asymmetry associated with a probability distribution of acoustic pressures, has been suggested to distinguish impulsive from non-impulsive underwater

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anthropogenic sounds (Martin *et al.*, 2020; Müller *et al.*, 2020). In addition to the two categories of sound types that are currently used to assess impacts of sound on marine mammals, psychoacoustic research on noise-induced threshold shifts (NITS) in humans has shown that a continuous spectrum of "impulsiveness" needs to be considered when evaluating kurtosis (Lei *et al.*, 1994; Zhao *et al.*, 2010; Qiu *et al.*, 2013; Suter, 2017).

This study applies the kurtosis analysis methods proposed by Martin *et al.* (2020) and Müller *et al.* (2020) to two real-world datasets collected during DTH pile driving and DTH pile drilling events associated with coastal construction projects in Alaska. To test the applicability of this approach for impact assessments of anthropogenic sound, the full datasets were used for the analyses.

2. Materials and methods

Acoustic datasets used for this study were collected during two in-water DTH pile installation activities: (1) DTH pile driving of two 0.46 m (18 in.) diameter steel pipe piles associated with a dock replacement project on Biorka Island, Alaska, in August 2018 (Guan and Miner, 2020) and (2) DTH pile drilling of two 0.84 m (33 in.) shafts within 1.22 m (48 in.) steel pipe piles during the construction of a new cruise ship dock in Ward Cove on the north side of Tongass Narrows in Alaska in June 2020 (Guan *et al.*, 2022). The first dataset is hereby referred to as the Biorka dataset (i.e., sounds from DTH pile driving) and the second dataset is referred to as the Ward Cove dataset (i.e., sounds from DTH pile drilling).

The Biorka dataset includes recordings collected at distances of 10 and 200 m from the piles, and the Ward Cove dataset includes recordings collected at distances of 10, 90, 150, 200, and 1300 m from the piles. Details of the data collection procedures, equipment, and settings are provided in Guan and Miner (2020) and Guan *et al.* (2022).

All acoustic recordings were divided into 1 min segments (see below for the rationale of using 1 min segments) and aurally and visually checked for presence of DTH hammer strike signals before calculating kurtosis values. If one or more hammer strike signals were detected in the 1 min segment, the sound clip was considered as "hammer on," otherwise, the clip was considered "hammer off" (see supplementary material for a summary of datasets used for the analysis).[1]

Custom MATLAB (MathWorks Inc., Natick, MA, version R2020a) scripts were used to calculate kurtosis (β),

$$\beta = \frac{T \cdot f_s \cdot \sum_{i=1}^{N} \left[p(i) - \bar{p}\right]^4}{\left\{\sum_{i=1}^{N} \left[p(i) - \bar{p}\right]^2\right\}^2}, \tag{1}$$

where f_s is the sampling frequency within a certain time interval T, $p(i)$ is the acoustic pressure, and $\bar{p}$ is the mean acoustic pressure within T.

From Eq. (1), it is obvious that β is dependent on T. While many of the studies in human psychoacoustics use a time interval of 40 s (e.g., Zhao *et al.*, 2010; Qiu *et al.*, 2013; Xie *et al.*, 2016; Zhang *et al.*, 2021), Martin *et al.* (2020) recommended a 1 min time interval in their investigation of using kurtosis to assess marine mammal sound exposure. Therefore, a 1 min time interval is used in this study to compare with results presented in Martin *et al.* (2020).

3. Results

The results show that the median kurtosis values for DTH pile driving are much greater (β ranged from 10.4–30.0) than those for DTH pile drilling (β ranged from 4.2–5.8). As expected for DTH pile driving, the median kurtosis values for the 1 min segments when the hammer was on (β ranged from 10.4–30.0) were much greater than when the hammer was off (β ranged from 4.3–4.9). However, the median kurtosis values for DTH pile drilling between hammer on and hammer off were approximately the same (β ranged from 4.2–5.8 and 3.2–5.8, respectively). Some examples of the waveforms and associated kurtosis values for DTH pile driving and DTH pile drilling are shown in Fig. 1. (See supplementary material for the summary results of median kurtosis values from both DTH pile driving and DTH pile drilling at different distances and during hammer on and off).[1]

Figure 2 shows kurtosis values superimposed with 1 s averaged sound exposure levels ($L_{\mathrm{E,\ 1\text{-}s}}$) during the entire DTH pile driving and DTH pile drilling events, respectively. To illustrate the majority of the data points that are around the median, kurtosis values above 40 are not displayed in Fig. 2. It is evident from the figure that the kurtosis values exhibited high variation. The boxplots in Fig. 3 provide a more detailed depiction of the β distributions. Although the middle half of the distributions cover a large range of kurtosis values for both DTH pile driving and pile drilling, the outliers are more numerous during DTH pile drilling. Results also indicate that kurtosis values for DTH pile driving during hammer on at 10 m (medians 21.4 and 30.0 for 13 and 15 August, respectively) are greater than the kurtosis value at 200 m (median 10.4), while kurtosis values during hammer off range from 4.3–4.9 when measured at any range. Conversely, for DTH pile drilling, there is no clear pattern for kurtosis values among the different distances and/or between hammer on and hammer off (Fig. 3).

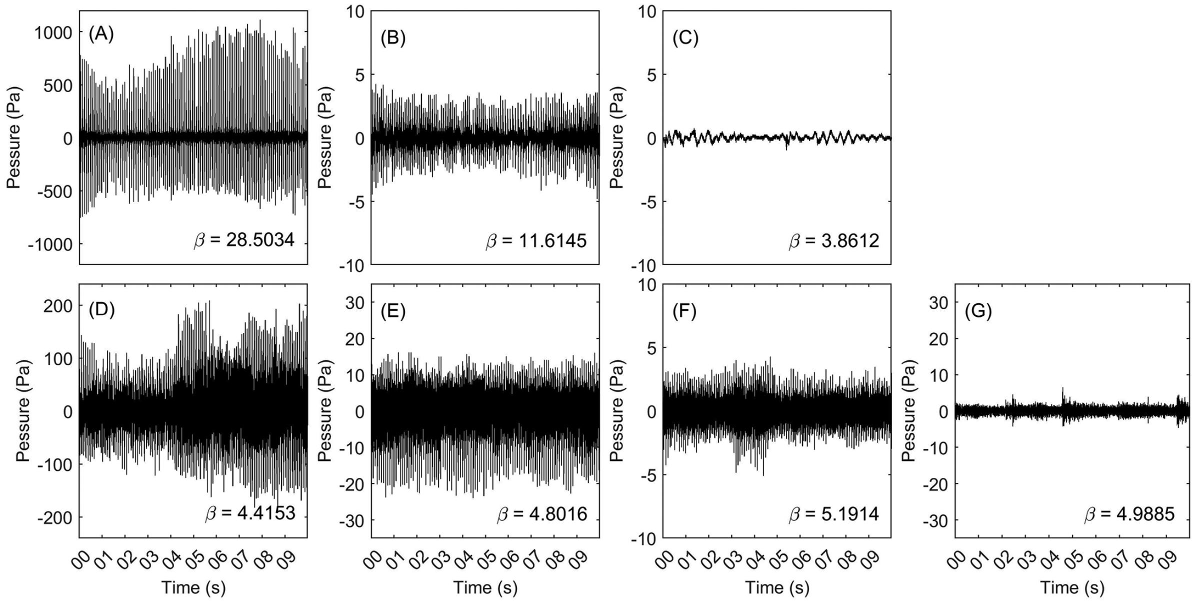

Fig. 1. Examples of the waveforms and associated kurtosis values (β) for DTH pile driving off Biorka Island on 13 August 2018 at distances of (A) 10 m and (B) 200 m when the hammer was on and (C) 200 m when the hammer was off and DTH pile drilling at Ward Cove on 19 June 2020 at distances of (D) 10 m, (E) 200 m, and (F) 1300 m when the hammer was on and (G) 200 m when the hammer was off.

4. Discussion

This study demonstrates the applicability of using kurtosis to categorize sound sources by determining the impulsiveness of *in situ* datasets of sound generated during DTH pile installation, which until recently has not been well studied (Guan and Miner, 2020; Guan *et al.*, 2022). The results from using 1 min acoustic data segments to calculate kurtosis

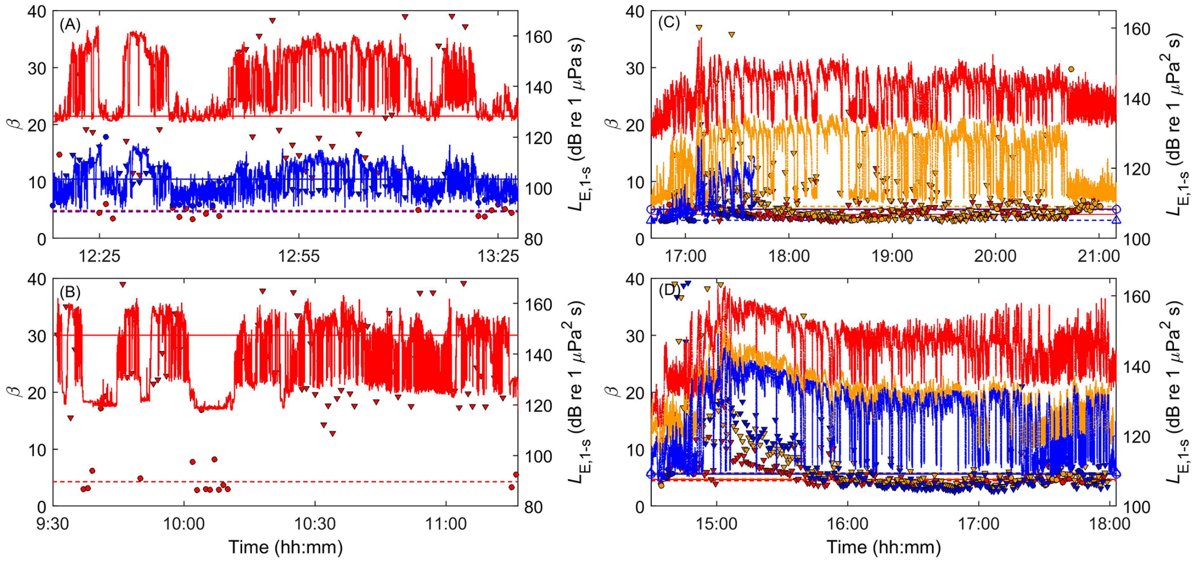

Fig. 2. Kurtosis values (β, left axis) and $L_{E,\ 1\text{-s}}$ (right axis) during each full DTH pile driving event off Biorka Island (A) 13 August and (B) 15 August 2018 and during each full DTH pile drilling event at Ward Cove on (C) 19 June and (D) 20 June 2020. Triangles indicate kurtosis values when the DTH hammer was on, and circles indicate kurtosis values when the hammer was off. For DTH pile driving at Biorka, red indicates a distance of 10 m, and blue indicates 200 m. For DTH pile drilling at Ward Cove, red indicates a distance of 10 m; orange indicates 200 m for 19 June and 90 m for 20 June, respectively; and blue indicates 1300 m for 19 June and 150 m for 20 June, respectively. For both pile driving and pile drilling, solid horizontal lines indicate median kurtosis values when the hammer was on, and dotted horizontal lines indicate when the hammer was off. Kurtosis values above 40 (11 out of 50 on 13 August 2018 at 10 m; 1 out of 50 on 13 August 2018 at 200 m; 22 out of 86 on 15 August 2018 at 10 m; 1 out of 43 on 19 June 2020 at 200 m during hammer off; 1 out of 42 on 19 June 2020 at 1300 m during hammer on; 3 out of 186 on 20 June 2020 at 90 m during hammer on; and 11 out of 184 on 20 June 2020 at 150 m during hammer on) are not shown.

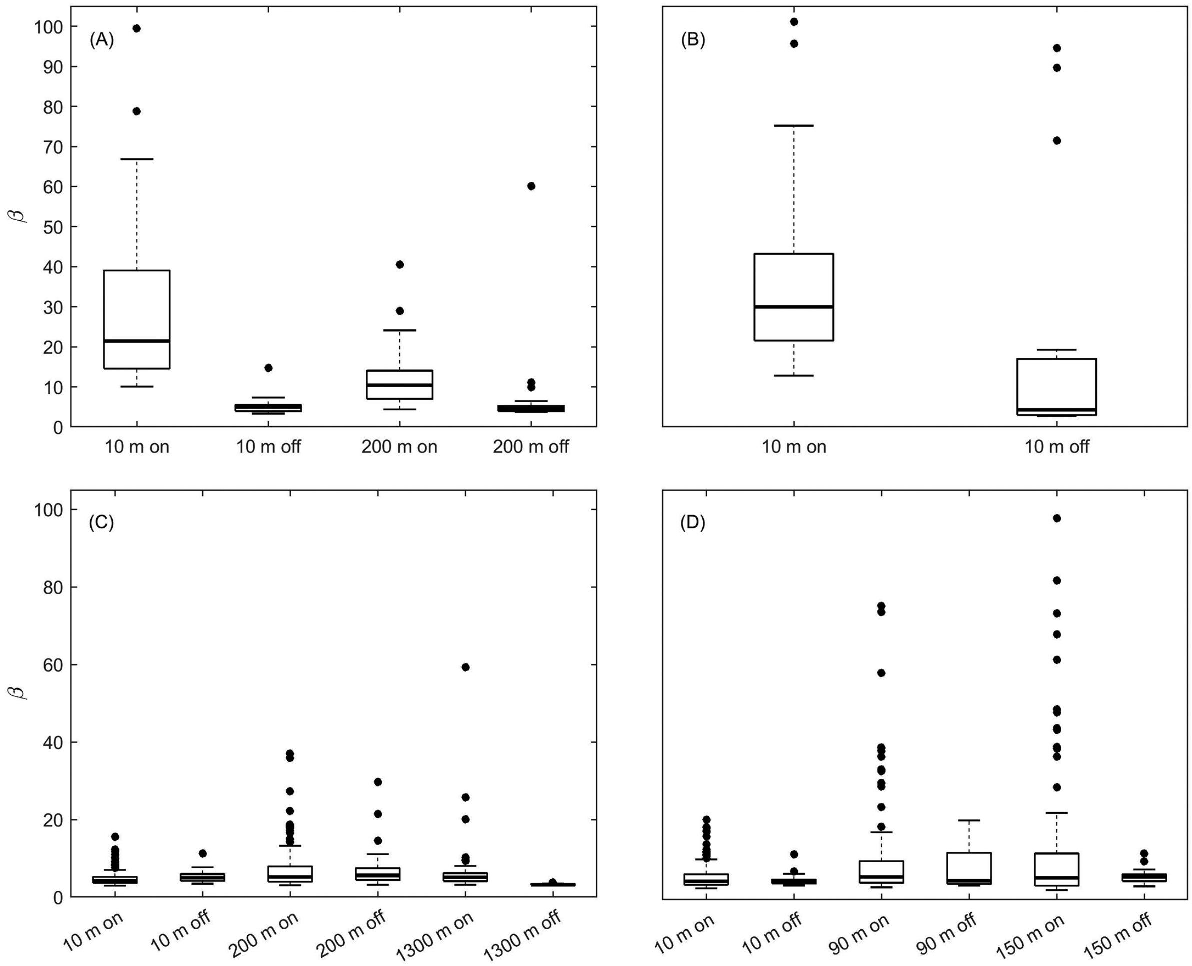

Fig. 3. Distributions of kurtosis values (β) for (A) DTH pile driving on 13 August 2018, (B) DTH pile driving on 15 August 2018, (C) DTH pile drilling on 19 June 2020, and (D) DTH pile drilling on 20 June 2020. "On" indicates when the DTH hammer was on, and "off" indicates when the hammer was off. The position of the box indicates the middle half of the distribution, and the bar inside the box indicates the median value. The horizontal lines below and above the box depict the lower and upper 25 percentiles, respectively. The circles above the box are outlier values.

values, as recommended by Martin *et al.* (2020), generally agree with our previous results that were based on the Harris (1998) method of using a 3 dB difference between the 35 ms and 1 s averaged $L_{\mathrm{p,rms}}$ to determine that sound emitted during DTH pile driving was more impulsive than that emitted during DTH pile drilling (Guan and Miner, 2020; Guan *et al.*, 2022).

Since the hammer strike frequencies for both DTH pile driving and DTH pile drilling are comparable (12–13 strikes per second for DTH pile driving and 10–12 strikes per second for DTH pile drilling), it is unclear why the sounds from DTH pile driving are so much more impulsive than those from DTH pile drilling (β ranged 21–30 at 10 m for DTH pile driving and 4–6 at 10 m for DTH pile drilling). One explanation could be based on the activities themselves, in which the hammer directly strikes the pile during DTH pile driving but does not do so during DTH pile drilling. The impulsiveness of the sound also could be affected by sediment and bedrock hardness, hammer depth, and/or propagation of sound directly into the water column vs only through the sediment.

Probability densities of the standard deviations of the acoustic pressure time series from randomly selected 20 min DTH pile driving and DTH pile drilling datasets at the various distances show that, while all data have leptokurtic distributions, a distribution with positive excess kurtosis, the shapes of DTH pile driving show more pronounced leptokurtic distributions than those of DTH pile drilling (Fig. 4), which are indicative of much greater kurtosis values during DTH pile driving than DTH pile drilling.

Using the 3 dB difference between the 35 ms and 1 s averaged $L_{\mathrm{p,rms}}$ for delineating impulsive vs non-impulsive sounds, DTH pile drilling sounds would have been categorized as non-impulsive (Guan *et al.*, 2022). However, kurtosis values between 4.20 and 5.81 and time series standard deviations with leptokurtic probability

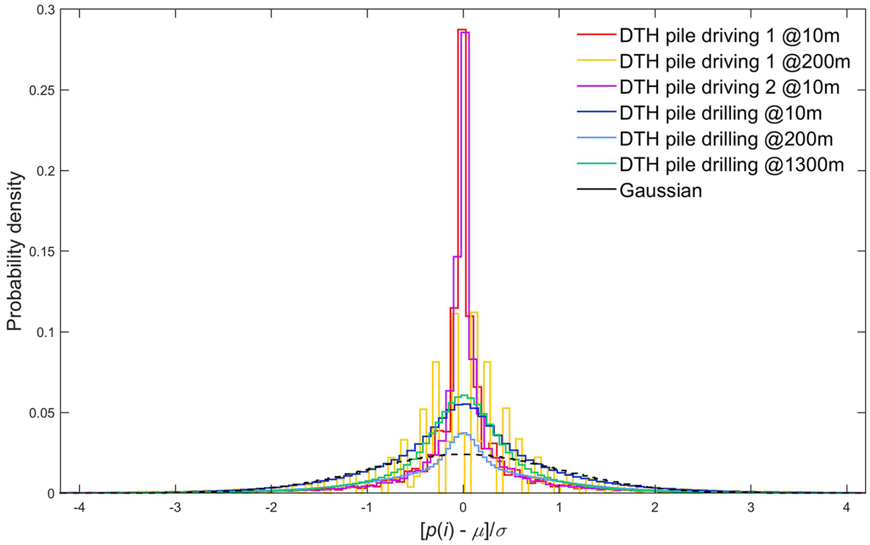

Fig. 4. Normalized probability densities of standard deviations of the acoustic pressure time series from several randomly selected 20 min DTH pile driving 1 (13 August 2018), DTH pile driving 2 (15 August 2018), and DTH pile drilling (19 June 2020) datasets at various distances where $p(i)$ is acoustic pressure, μ is the mean, and σ is the standard deviation. These plots show that DTH pile driving events have more pronounced leptokurtic distributions than DTH pile drilling events.

distributions indicate that those sounds are not Gaussian. Given that kurtosis of Gaussian-distributed random data is 3 (Balandra and MacGillivray, 1988), Martin *et al.* (2020) observed that data with transient sounds have kurtosis values greater than 3. Nevertheless, because of the high variability of the acoustic environment during the actual construction activity, kurtosis values for DTH pile drilling during the timeframe when the DTH hammer was off were not always less than those when the hammer was on. The higher kurtosis values when the hammer was off were likely due to other sounds, such as pumping and airlifting of cuttings and debris, which may not be steady state due to the changes in the various machinery power outputs. However, the specific sources that were operating during hammer off periods were not able to be identified.

These observations present an interesting issue concerning the application of marine mammal temporary threshold shift (TTS) thresholds obtained from laboratory-controlled experiments to real-world situations. Most marine mammal NITS studies involving non-impulsive sound exposure were conducted using digitized steady-state tonal or banded signals with unknown kurtosis values (Finneran, 2015; Kastelein *et al.*, 2019; Kastelein *et al.*, 2020a; Kastelein *et al.*, 2020b).

Martin *et al.* (2020) suggested that a 1 min sound pressure time series with a kurtosis value greater than 40 for frequency-weighted sounds should be considered fully impulsive based on human and terrestrial animal studies. The unweighted kurtosis values for DTH pile driving were greater than 20–30 at 10 m and approximately 10 at 200 m from the pile, indicating that they are not as impulsive as similarly unweighted sounds from impact pile driving or geophysical seismic surveys at close range (Martin *et al.*, 2020). The impulsive structure of DTH pile driving is evident, but much less so for DTH pile drilling. These results also suggest a wide spectrum of "impulsiveness" between fully impulsive and steady-state non-impulsive sounds.

The impulsiveness of a sound in relation to distance is an interesting topic requiring additional research (Guan *et al.*, 2021). Delineation of kurtosis values at various distances as an indication of impulsiveness may be a promising starting point for such studies.

In the wild, marine mammals are exposed to complex sound fields from human activities that contain both impulsive and non-impulsive structures. Aside from the sounds generated from DTH pile installation discussed herein, examples of other real-world situations include in-water impact pile driving (impulsive) from a barge operating a dynamic positioning system (non-impulsive), concurrent impact (impulsive) and vibratory (non-impulsive) pile driving activities, or in-ice geophysical seismic survey (impulsive) accompanied by an icebreaker (non-impulsive).

Human and terrestrial mammal studies have determined that exposure to complex sound is more detrimental than steady-state non-impulsive sound at the same sound exposure level (Ahroon *et al.*, 1993) and that kurtosis of a sound field can be a useful metric for determining TTS thresholds associated with exposure to complex sound (Hamernik *et al.*, 2003; 2007; Zhao *et al.*, 2010; Qiu *et al.*, 2013; Xie *et al.*, 2016). However, NITS studies of marine mammals (or any marine species) exposed to complex sound have yet to be conducted. Such research is urgently needed to understand NITS of marine mammals from anthropogenic sound in numerous real-world situations that involve complex sound

(Guan and Brookens, 2021). In addition, NITS studies involving marine mammals exposed to the same L_E at differing kurtosis values are needed to examine whether onset threshold shifts would be affected.

5. Conclusion

This study used kurtosis analysis methods to characterize the impulsiveness of sounds generated from DTH pile driving and DTH pile drilling. The results confirm our previous findings that sounds from DTH pile driving are more impulsive than those from DTH pile drilling. However, the results also indicate that, based on the suggested delineations of Martin *et al.* (2020), sounds from DTH pile driving are not fully impulsive and sounds from DTH pile drilling are not purely non-impulsive.

In addition, the results from DTH pile drilling underscore that anthropogenic sound fields experienced by marine mammals in the wild often contain various levels of impulsiveness due to the presence of other construction sounds. In the case of DTH pile drilling, the elevated kurtosis value during the timeframe the hammer was off could be the result of sound emitted from pumping and airlifting of cuttings and debris.

Finally, studies in human and terrestrial mammal NITS have shown that exposure to complex sounds that include both impulsive and non-impulsive components is more detrimental than exposure to steady-state non-impulsive Gaussian sound. However, almost all NITS studies on marine mammals exposed to non-impulsive sources have used digitized tonal or banded signals. Such sound fields may not reflect the acoustic environment that the animals normally would encounter when exposed to anthropogenic activities. Thus, TTS studies involving marine mammals exposed to complex sound should be conducted to determine whether it is appropriate to continue to promulgate the current U.S. regulatory dichotomy that distinguishes only two sound source categories.

Acknowledgments

The authors thank Turnagain Marine Construction, Inc., and Solstice Alaska Consulting, Inc., for supporting collection of the acoustic recordings. We also thank Paulina Chen, Rodney Cluck, Alexander Conrad, Samuel Denes, Yoko Furukawa, Hilary Kates Varghese, Stanley Labak, Peter Thomas, and an anonymous reviewer for their constructive comments on the manuscript.

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[1] See supplementary material at https://www.scitation.org/doi/suppl/10.1121/10.0012348 for a summary of datasets used for the analysis and for the summary results of median kurtosis values from both DTH pile driving and DTH pile drilling at different distances and during hammer on and off.

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