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Underwater noise characterization of down-the-hole pile driving activities off Biorka Island, Alaska

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ABSTRACT

Although down-the-hole (DTH) pile driving is increasingly used for in-water pile installation, the characteristics of underwater noise from DTH pile driving is largely undocumented and unstudied. This study presents a comprehensive analysis of the noise characteristics during DTH pile driving of two steel pipe piles in shallow waters off southeast Alaska. The results showed that single-strike sound exposure levels measured at 10 m were 147 and 145 dB re 1 μPa^{2}s with a total of 21,742 and 38,631 hammer strikes, with cumulative sound exposure levels to install each pile at 192 and 191 dB re 1 μPa^{2}s, respectively. Though noise levels from a single strike was lower than impact pile driving of a similar pile, the cumulative sound exposure levels are likely comparable due to the much higher striking rate.

1. Introduction

The intense noises generated from in-water pile driving associated with coastal and offshore construction activities are known to have adverse effects on marine organisms (Bailey et al., 2010; Dahl et al., 2015). Potential adverse effects range from behavior alteration (Tougaard et al., 2009; Kendall and Cornick, 2016; Herbert-Read et al., 2017; Branstetter et al., 2018), habitat displacement (Dähne et al., 2013), and hearing impairment (Kastelein et al., 2015; Kastelein et al., 2016; Kastelein et al., 2018), to physical injury and mortality (Casper et al., 2012; Casper et al., 2013a; Halvorsen et al., 2012). Because of such concerns, extensive programs of measurement and analysis of the sounds have been undertaken during the past 20 years (*e.g.*, (Buehler et al., 2015; Amaral et al., 2020)). The results of such measurements and analyses are used by project proponents to obtain permits or authorizations and comply with regulations, and by government regulators to conduct environmental impact assessments (*e.g.*, (Thompson et al., 2013; Andersson et al., 2016)).

The two most common methods of advancing steel piles are impact and vibratory pile driving. Impact pile driving involves striking the top of a pile to generate a relatively large downward traveling compressive stress wave in the pile. Vibratory driving involves imparting vibrational energy to the top of the pile; this energy temporarily weakens soil resistance and a modest net downward or upward force advances or extracts the pile. There are circumstances when a pile is first advanced with a vibratory hammer and then driven to the final tip elevation using an impact hammer. Some piles, particularly temporary piles are vibrated to near final depth, and then briefly "proofed" with an impact hammer.

Impact pile driving produces intense impulsive sound that is characterized by a fast rise time, followed by a rapid decay in acoustic pressure. Sound pressure levels (SPLs) measured from impact pile driving depend on many factors, the most significant of which are typically the pile type (timber, concrete, or steel), the pile diameter and energy output of the impact hammer (Reinhall and Dahl, 2011; Zampolli et al., 2013; Lippert and von Estorff, 2014; Lippert et al., 2016). For example, impact pile driving of an approximate 0.92-m (36-in) diameter steel pipe pile can produce a peak sound pressure level ($L_{\mathrm{p,pk}}$) of 210 dB re 1 μPa, a root-mean-square (rms) sound pressure level ($L_{\mathrm{p,rms}}$) (see ISO 18405:2017 for the definition of acoustic units (ISO, 2017a)) of 193 dB re 1 μPa, and a single-strike sound exposure level ($L_{\mathrm{E,ss}}$) of 183 dB re 1 μPa^{2}s, all at a distances of 10 m from the pile (Buehler et al., 2015). Commonly used impact hammers usually strike the pile at a rate of approximately 0.6 to 1.5 strikes per second. In comparison, vibratory hammers typically oscillate at much higher rates and cause non-impulsive, continuous sounds that have lower acoustic pressure. For example, typical $L_{\mathrm{p,rms}}$ during vibratory pile driving of an approximate 1 m (36-in) diameter steel pipe pile in 5 m of water was 175 dB re 1 μPa at 10 m (Buehler et al., 2015). These different acoustic metrices ($L_{\mathrm{p,pk}}$, $L_{\mathrm{p,rms}}$, and $L_{\mathrm{E,ss}}$) are used by regulatory agencies to

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assess different levels of impacts for marine fauna. The readers are referred to specific regulatory guidelines and standards (*e.g.*, (Southall et al., 2007; Popper et al., 2014; Scholik-Schlomer, 2015; NMFS, 2018; Southall et al., 2019)) for the use of these metrices in environmental impact assessments.

Because impact and vibratory hammers have long been the nearly exclusive choices for in-water pile installation, almost all studies on pile driving sound to date have been limited to those two methods (*e.g.*, (Buehler et al., 2015; Illingworth, and Rodkin, Inc, 2012; Austin et al., 2016; Soderberg and Laughlin, 2016)).

Over the past few years, a new type of technology called down-the-hole (DTH) pile driving has made its way into coastal and offshore construction, particularly in conditions where the soil overlying rock is too shallow to allow piles to terminate with sufficient resistance to lateral or tensile loads (*i.e.*, horizontal or rotational forces acting on the piles). DTH pile driving uses a combination of percussive and drilling mechanisms, with the hammer acting directly on the rock to advance a hole into the rock, and also advance the pile into that hole. Drill cuttings and debris at the rock face are removed by an air-lift exhaust up the inside of the pile. Based on different mechanisms applied by several industrial entities, DTH pile driving activities also have been referred to as “DTH drilling” (*e.g.*, (Dazey et al., 2012; Warner et al., 2016)), “DTH hammering” (*e.g.*, (Denes et al., 2019)), “rock socket drilling” (*e.g.*, (Denes et al., 2016; Reyff and Heyvaert, 2019)), and “rock anchor drilling” (*e.g.*, (Reyff and Heyvaert, 2019)). DTH pile driving is considered one of the fastest ways to drill through hard rock for pile installation and is, therefore, finding increased application in marine construction.

To date, measurements of DTH pile driving sound levels, its near source characteristics, and associated sound propagation are only found in two technical reports (Denes et al., 2019; Reyff and Heyvaert, 2019). In addition, Denes et al. (2016) and Dazey et al. (2012) provided general averaged sound levels (1 s and 30 s averages, respectively) that were measured during coastal construction projects off Kodiak Island, Alaska, and Santa Rosa Island, California, respectively, during DTH pile driving. However, their studies did not report detailed, per-pulse characteristics of the DTH pile driving sound (*i.e.*, $L_{\mathrm{E,ss}}$ or $L_{\mathrm{p,rms}}$ of each pulse).

The intent of this paper is to increase understanding of DTH pile driving by providing details on near source (10 m) levels and noise characteristics based on *in situ* measurements conducted during DTH pile driving activities associated with a dock replacement project undertaken by the Federal Aviation Administration on Biorka Island, Alaska (Fig. 1).

2. Materials and methods

2.1. Field recording

The study site was located approximately 24 km southwest of Sitka on the northern shore of Biorka Island in Symonds Bay in Alaska (ECO49, 2017) (Fig. 1). The piles that were installed were approximately 15 m long and 0.46 m (18 in.) in diameter open-end steel pipe piles. The piles were first advanced by self-weight through a very thin layer of soft or loose soil, then driven into hard bedrock using a DTH hammer to approximately 3 m depth. This context well represents the conditions wherein DTH methods are relevant. The DTH hammer was a Patriot® 125 hammer manufactured by Numa (Thompson, CT, USA). The hammer operated inside the pipe pile by the combined action of a percussive rotating bit acting on the rock with modest impact forces on the pile shoe (the iron casing that is fitted to the lower end of the pile), pulling the pile into the advancing drilled hole. Drill cuttings were removed by an air-lift exhaust up the interior of the pile.

Underwater sound measurements were conducted on two of the steel pipe piles (F14 and E14) driven on 13 August 2018 between 12:20 and 13:20 and on 15 August between 09:30 and 11:10. In making these measurements, the authors consulted with the ISO 18406:2017 Underwater Acoustics – Measurement of Radiated Underwater Sound from Percussive Pile Driving (ISO, 2017b) and conformed to its requirement in certain measurement standards. Acoustic recordings were made using three hydrophones at approximately 10, 200, and 1200 m from Pile F14 on 13 August and at approximately 10 and 1200 m from the Pile E14 on 15 August. Each hydrophone was attached to an anchor, which sat on the seafloor; the buoyant hydrophone rose above the anchor to depth that was approximately 0.7 to 0.8 times the water depth. Water depth was 3–4 m at the 10 m location, 7–9 m at the 200 m location, and 15 m at the 1200 m location.

The hydrophone used at the 10-m location was a Reson Model TC 4040; while those at the 200 and 1200 m locations were Reson Model TC4033. Each hydrophone was connected to a Brüel & Kjær Model 2635 charge amplifier which provided conditioned signals to a Brüel & Kjær Model 2270 Class 1 sound level meter (SLM) with a sampling rate of 48 kHz. The SLM continuously recorded the time series measurements for subsequent analysis. The receiving sensitivity of the hydrophone at 10-m was −206 dB re 1 V/μPa. At the 200 and the 1200 m, the hydrophone receiving sensitivity was −203 dB re 1 V/μPa. All recordings were saved in.wav format on SD cards. A GRAS 42 AC high pressure pistonphone sound source provided field verification of system function, gain settings, and replay factors.

2.2. Data analysis

Acoustic data were analyzed using custom written MATLAB (version 2020a) scripts. Time-varying SPLs based on 1 s averages, cumulative sound exposure levels ($L_{\mathrm{E},cum}$), and spectrograms of the entire pile driving duration were computed over the frequency range between 10 and 22,000 Hz, and plotted for both piles at all distances as a basis for visual inspection and preliminary review. Spectrograms were generated using a fast Fourier transform size of 10,240 and a window size of 10,240 with 50% overlap. Very few hammer strikes were detected at a distance of 1200 m, therefore, recordings collected at 1200 m were excluded from further analysis.

For recordings collected during F14 pile driving events at 10 and 200 m and E14 at 10 m, $L_{\mathrm{p,rms}}$ was computed for each strike. The $L_{\mathrm{p,rms}}$ metric comprises 90% of the acoustic energy in the strike and was calculated using Eq. (1) based on Madsen (2005) (Madsen, 2005).

$$L_{p,rms} = 10\log_{10}\left(\frac{1}{\mathrm{T}}\int_{T} p(t)^2 \mathrm{d}t\right) \tag{1}$$

where $p(t)$ is the instantaneous acoustic pressure (Urick, 1983) and T is the pulse duration that comprises the middle 90% of the acoustic energy.

$L_{\mathrm{p,pk}}$ and $L_{\mathrm{E,ss}}$ also were calculated for both piles at the 10 and 200 m distances for F14 and at the 10 m distance for E14. In addition, power spectral densities (PSDs) of a single strike recorded at these distances were computed to investigate the frequency content of the pulses.

3. Results

A total of 560 min of recordings were obtained during the pile driving events on 13 and 15 August 2018. DTH pile driving of F14 on 13 August took approximately 62 min, which included 21,742 hammer strikes. DTH pile driving of E14 took approximately 109 min with 38,631 hammer strikes on 15 August. Percussive hammering was intermittent over these time periods.

The $L_{\mathrm{p,rms}}$, $L_{\mathrm{E},cum}$, and spectrograms of the entire pile driving durations at distances of 10 and 200 m for Pile F14 and at 10 m for Pile E14 are shown in (Figs. 2 and 3), respectively. Detailed plots of acoustic pressure, SPLs, and the spectrogram of a 2 s segment of representative percussive pulses at the 10-m distance are shown in (Fig. 4). The spectrograms in (Figs. 2 through 4) indicate that most of the acoustic energy from DTH pile driving is below 2 kHz. At above 2 kHz, near

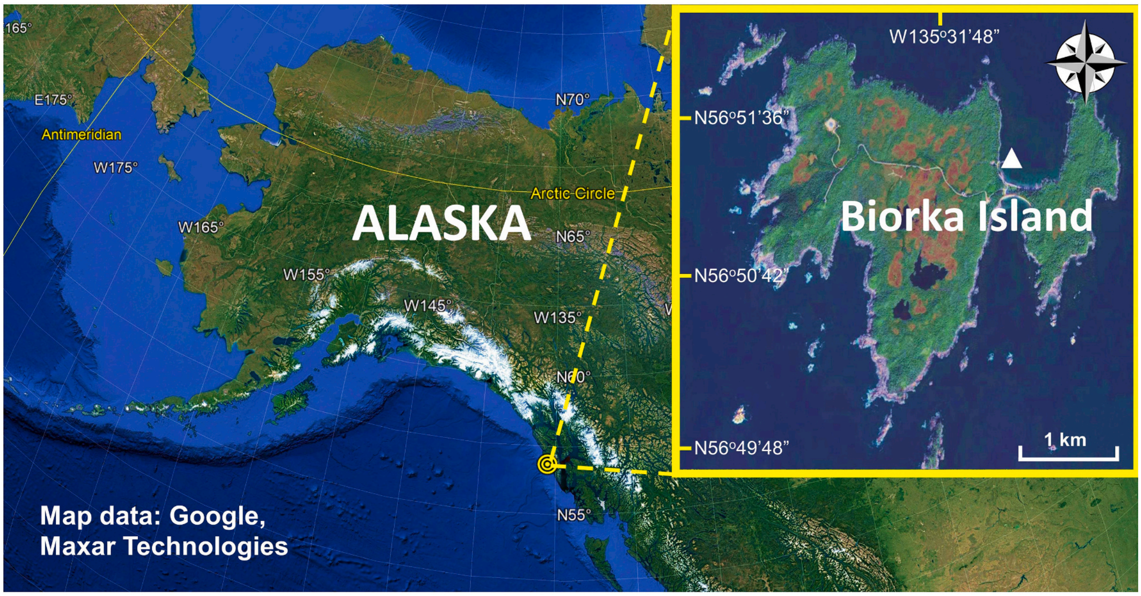

Fig. 1. Map of the study area. The white triangle indicates the dock replacement location on Biorka Island, Alaska, where in-water DTH pile driving occurred.

source (10 m) noise levels decrease at a rate of approximately 20 dB/decade. This also is supported in the PSD plot in Fig. 5. Unlike conventional impact pile driving, in which the hammer strikes a pile at a rate of approximately 0.6–1.5 strike per second, a DTH hammer strikes at a much faster rate of 10–14 strikes per second (Fig. 4).

All noise levels were computed within the frequency range of 10 to 22,000 Hz. At the 10 m distance, the median $L_{\mathrm{p,rms}}$ during DTH pile driving for F14 and E14 were 162 and 161 dB re 1 μPa, respectively. The median values of $L_{\mathrm{E,ss}}$ at 10 m for F14 and E14 were 147 and 145 dB 1 μPa^{2}s, respectively. Fig. 6 shows the distribution of $L_{\mathrm{E,ss}}$ and CDF for F14 and E14. The $L_{\mathrm{E},cum}$ for F14 and E14 were 192 and 191 dB re 1 μPa^{2}s, respectively. At the 200-m distance, the median $L_{\mathrm{p,rms}}$ for Pile F14 was 140 dB re 1 μPa; the $L_{\mathrm{E,ss}}$ and $L_{\mathrm{E},cum}$ were 127 and 171 dB re 1 μPa^{2}s, respectively. Descriptive statistics of the $L_{\mathrm{p,rms}}$ and $L_{\mathrm{E,ss}}$ for all analyzed acoustic data are reported in Table 1.

4. Discussions

Although DTH pile driving has been increasingly employed by the industry to install piles in areas that are dominated by bedrock substrate, only a few studies have measured and characterized DTH pile driving sound in detail (*e.g.*, Denes et al., 2019 (Denes et al., 2019); Reyff and Heyvaert, 2019 (Reyff and Heyvaert, 2019)). This study provides the first glimpse on the details of the noise levels and characteristics from DTH pile driving. One of the notable characteristics is that noises from DTH pile driving strongly resemble those of impact pile driving, but with a much higher hammer striking rate (approximate 10 Hz or higher). Our study also shows that dominant frequencies from DTH pile driving are below 2.5 kHz, which is similar to conventional impact and vibratory pile driving. In addition, as indicated in the time series plot and spectrogram (Fig. 4), due to the high rate of hammer striking and drilling and debris clearing out, noise levels between the pulses are much higher than convention impact pile driving.

Dazey et al. (2012) appears to have reported the first instance of DTH pile driving (described as DTH drilling by the authors) during in-water construction work for a pier replacement off Santa Rosa Island, California. However, the authors did not provide any description of the sound characteristics for either aspect of the source or the type and size of piles installed. They used a simple cylindrical spreading model to calculate the source level based on where recordings were made and derived mean source levels of 150.5 and 154.2 dB re 1 μPa based on 30 s averages for the two seasons in their study. Dazey et al. (2012) did

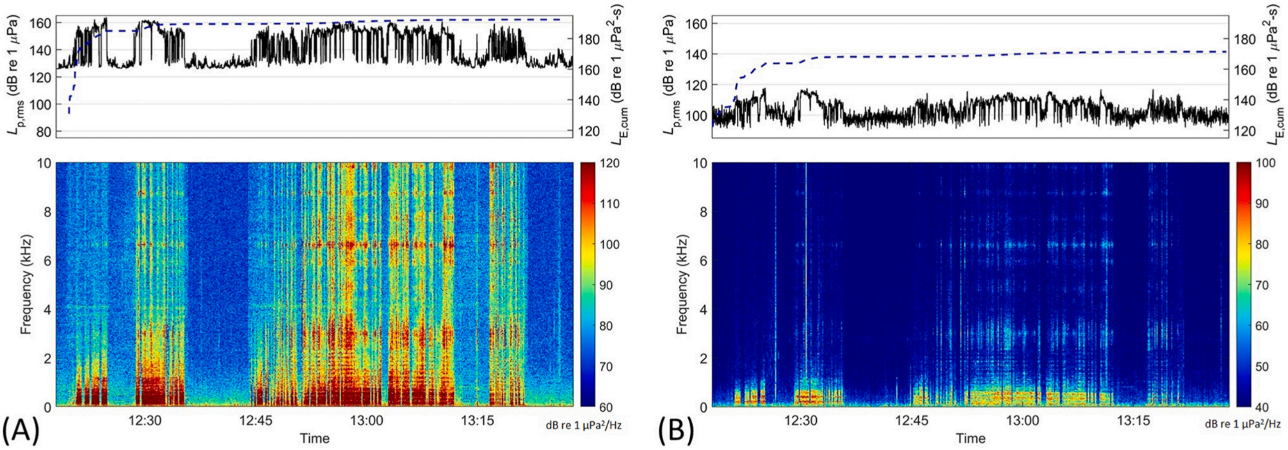

Fig. 2. Sound pressure levels (upper plot, black solid line), cumulative sound exposure levels (upper plot, blue dashed line), and spectrograms (lower plot) of DTH pile driving of Pile F14 recorded at a distance of 10 m (A) and 200 m (B) on 13 August 2018. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

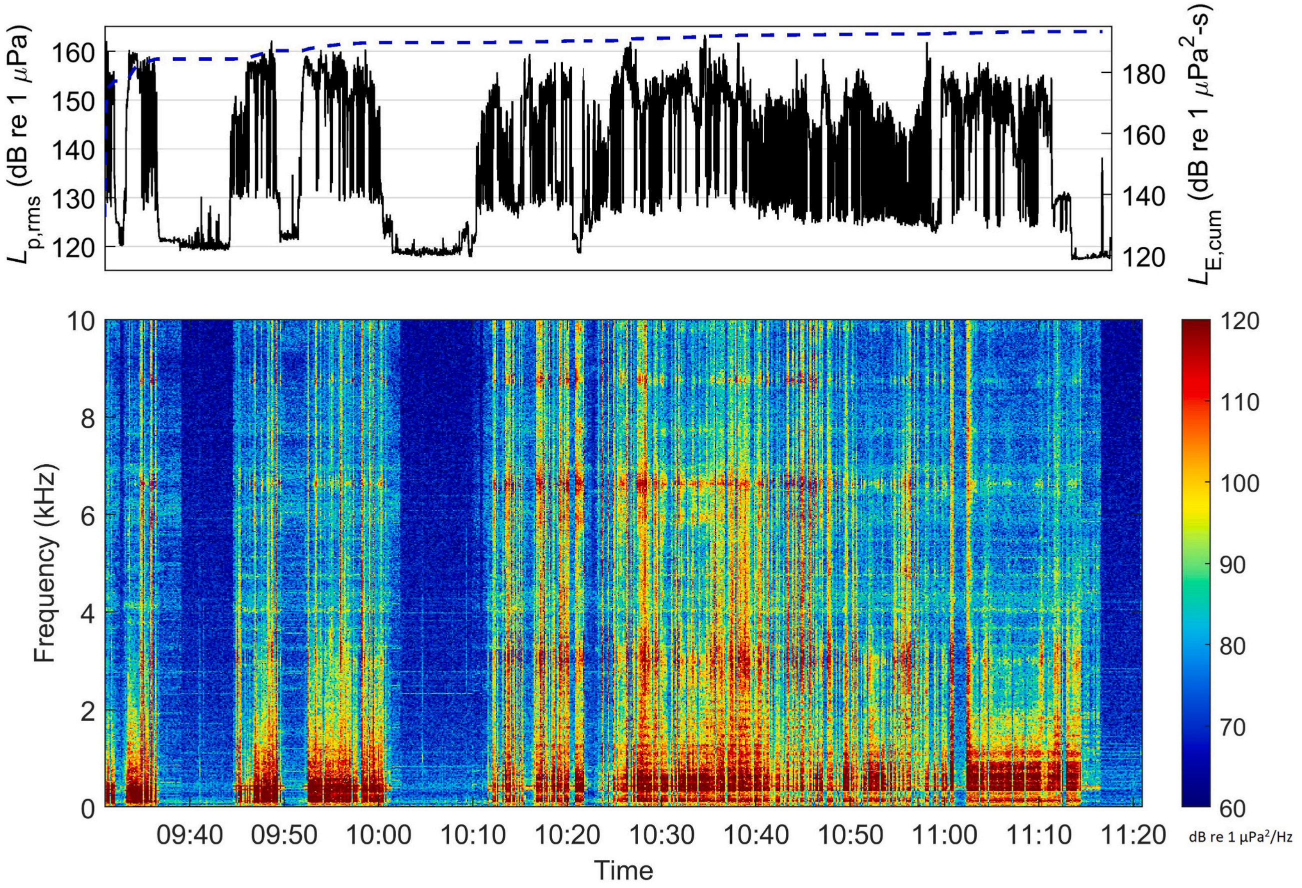

Fig. 3. Sound pressure levels (upper plot, black solid line), cumulative sound exposure levels (upper plot, blue dashed line), and a spectrogram (lower plot) of DTH pile driving of Pile E14 recorded at a distance of 10 m on 15 August 2018. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

not provide in depth per-pulse sound level analyses.

Denes et al. (2016) reported sound levels associated with DTH pile driving (described as rock socket drilling or DTH drilling by the authors) during installation of eight 0.61 m (24 in.) diameter, 21.03 m (69 ft) long, steel pipe piles for the construction at the Kodiak Ferry Terminal in 2016. The authors noted that sound levels from DTH drilling were dominated by sounds produced by the drill's hammer at the pile toe and that the hammer struck the pile toe at a rate of approximately 15.5 Hz. However, they did not provide in depth per-pulse analysis of each hammer strike. Instead, the authors treated the sounds as continuous and reported a back-calculated (by curve fitting of measurements at different distances) $L_{p,rms}$ 10 m noise level of 166 dB re 1 μPa based on 1 s averages.

Reyff and Heyvaert (2019) measured DTH pile driving (described as rock socket drilling and rock anchor drilling by the authors) of 1.07 m (42 in.) diameter, 91.44 m (300 ft) long, steel pipe piles used for mooring dolphins at the White Pass & Yukon Route's Railroad Dock in Skagway, Alaska, in 2019. The authors noted that sounds from the activities cycled through various levels of drilling with intermittent hammering and debris clean out. They also reported that the rapid hammering for rock socket drilling occurred at a rate of 10 strikes per second. The authors initially treated the noises as continuous sounds and the measurement approach was designed to capture continuous sounds in fixed 1 s time intervals during the activity. The computed 1 s L_E and $L_{p,rms}$ at 10 m from the source where hammering and drilling actions occur (*i.e.*, the slant range) were 179 dB re 1 μPa^{2}s and 184 dB re 1 μPa, respectively; whereas, the calculated L_E and $L_{p,rms}$ at 10 m that represent the horizontal range from the pile were 174 dB re 1 μPa^{2}s and 178 dB re 1 μPa, respectively. The $L_{E,ss}$ was estimated based on the hammer rate of 10 Hz, which was 164 dB re 1 μPa^{2}s (Reyff, 2020).

Most recently, Denes et al. (2019) conducted DTH pile driving (described as DTH hammering by the authors) measurements at Thimble Shoal along the Chesapeake Bay Bridge Tunnel in Virginia during installation of casings for 1.07 m (42 in.) diameter dock piles in 2019. The results showed that median back-calculated $L_{E,ss}$ and $L_{p,rms}$ at 10 m were 163 dB re 1 μPa^{2}s and 180 dB re 1 μPa, respectively.

A comparison between our measurements and those reported by Reyff and Heyvaert (2019) and Denes et al. (2019) is summarized in Table 2.

The near source (10-m) levels reported for Skagway (Reyff and Heyvaert, 2019) and Thimble Shoal (Denes et al., 2019) were greater than our measurements at Biorka most likely due to the larger diameter of the piles at those two sites. DTH pile driving at Skagway and Thimble Shoal were conducted on piles of 1.07 m in diameter, while in our study, the piles were only 0.46 m in diameter. The small diameter of the pile indicates a smaller area where hammering energies are exerted on the bedrock. In addition, the differences in water depth (35–37 and 17 m *vs.* 3–4 m) at the location where pile driving took place is also expected to contribute to the difference in sound levels. Lower frequency sound with longer wavelength in relation to water depth could experience "low-frequency" cufoff, thus does not propagate efficiently in shallower water (Etter, 2013).

Other factors that may affect the sound levels during DTH pile driving may include the type of rocks that comprise the substrate, bit size of the DTH hammer, and pile diameter. However, at this point we do not have sufficient data to investigate the impacts of these factors on the sound levels measured.

Many studies have addressed various aspects of how noise from in-

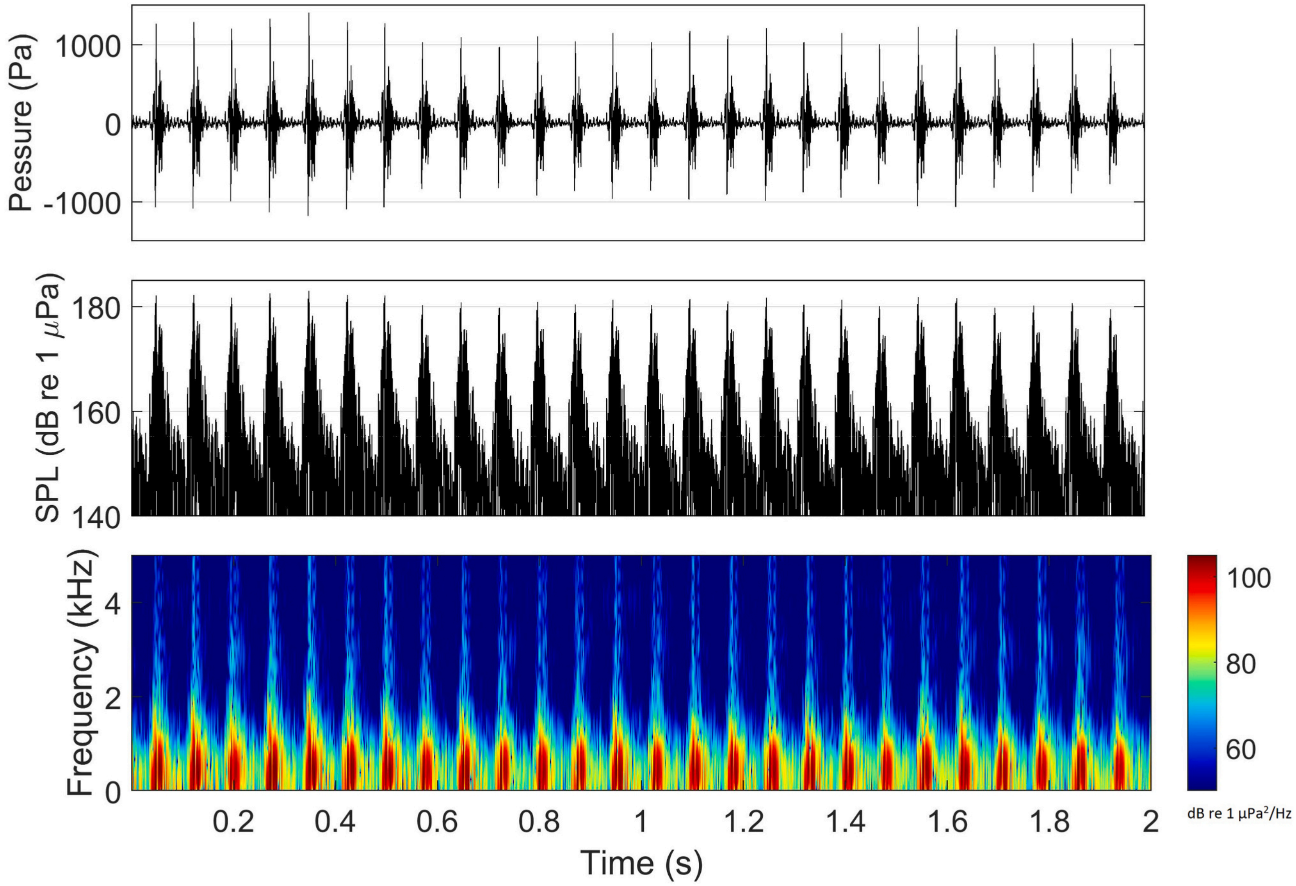

Fig. 4. Details of a 2 s segment of DTH pile driving showing the time series of acoustic pressure (top), sound pressure levels (middle), and spectrogram (bottom).

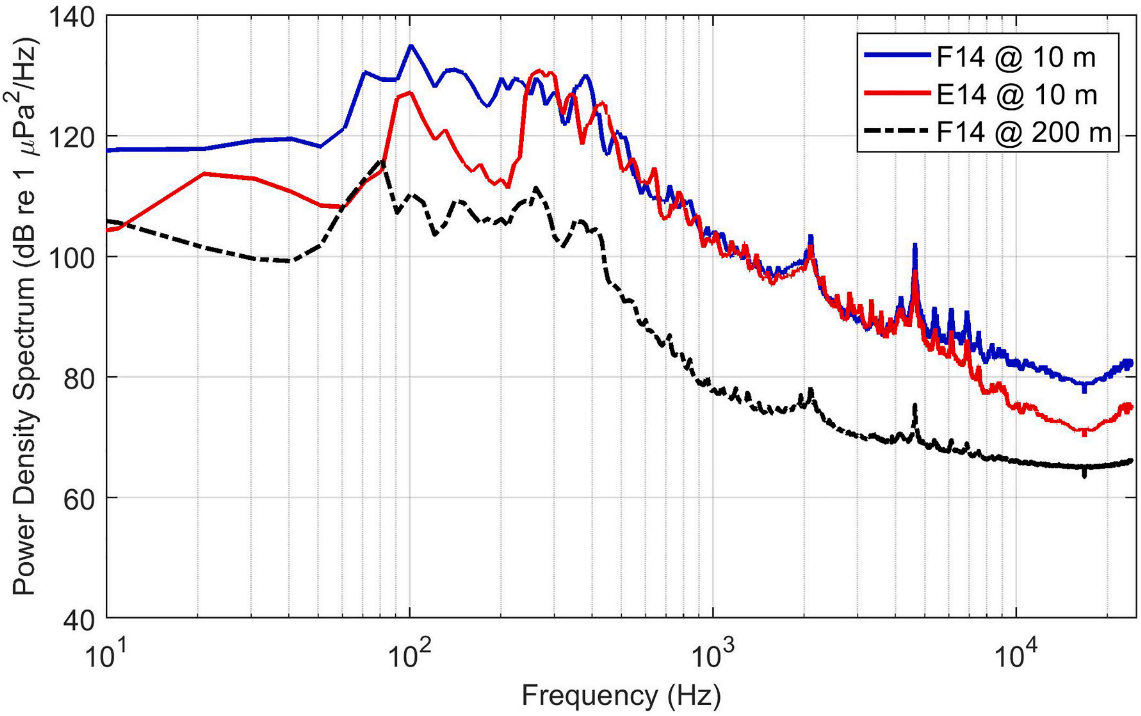

Fig. 5. Median power spectral density of measured DTH pile driving sound.

water pile driving may have detrimental effects on marine life. Most studies pertain to noise from impact pile driving (*e.g.*, (Tougaard et al., 2009; Herbert-Read et al., 2017; Dähne et al., 2013; Kastelein et al., 2015; Kastelein et al., 2016; Kastelein et al., 2018; Halvorsen et al., 2012; Popper and Hastings, 2009; Casper et al., 2013b; Graham et al., 2019; Jones et al., 2020)). A few studies have addressed underwater

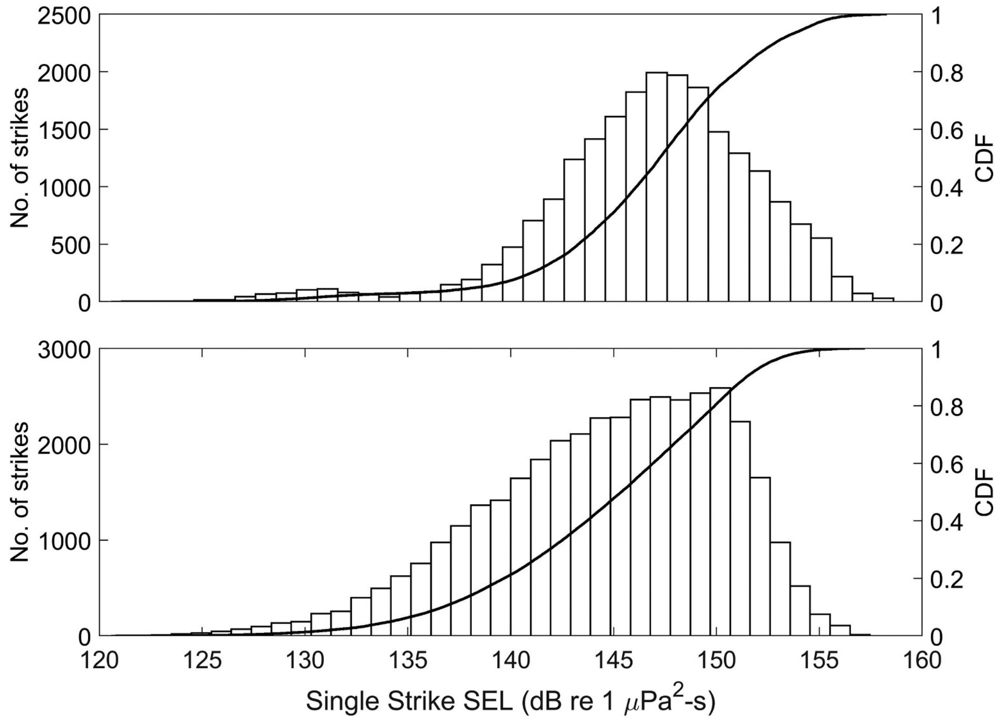

Fig. 6. Single-strike sound exposure levels and cumulative density function (CDF) of DTH pile driving strikes for pile F14 (top) and E14 (bottom) measured at 10 m from the piles.

Table 1

Descriptive statistics of DTH pile driving measurements for Piles F14 (13 August 2018) and E14 (15 August 2018) at 10 m and Pile F14 at 200 m.

Acoustic parameters	F14 (10 m)	F14 (200 m)	E14 (10 m)
Median $L_{E,ss}$ (dB re 1 μPa^{2}s)	147	127	145
$L_{E,cum}$ (dB re μPa^{2}s)	192	171	191
Median $L_{p,rms}$ (dB re 1 μPa)	162	140	161
Median $L_{p,pk}$ (dB re 1 μPa)	173	148	170
Median rms pulse duration (ms)[a]	32	49	27

[a] Median rms pulse duration is defined as the 50th percentile of the duration that encompasses the 90% energy window of the pulse.

Table 2

Comparison of near-source (10-m) measurements among three studies.

Acoustic parameters	Biorka	Skagway[a]	Thimble shoal
$L_{E,ss}$ (dB re 1 μPa^{2}s)	145–147	164	163
$L_{E,cum}$ (dB re 1 μPa^{2}s)	191–192	207	Not reported
$L_{p,rms}$ (dB re 1 μPa)	161–162	178	180
Hammer strike rate (strikes/s)	13	10	7
Pile diameter (m)	0.46	1.07	1.07
Water depth (m)	3–4	35–37	17

[a] The Skagway metrics were based on 1 s averages rather than per-pulse metrics as reported for Biorka and Thimble Shoal.

noise impacts from vibratory pile driving (*e.g.*, (Branstetter et al., 2018; Wang et al., 2014)). These studies of impact and vibratory driving indicate that under specific circumstances the effects from pile driving noise may include behavioral modification or disturbance, habitat displacement, auditory masking, hearing threshold shifts, and in the case of fish and marine invertebrates, potential physical injury and mortality. To date, the effects upon marine life of noise from DTH pile driving has not be studied. Nevertheless, it is reasonable to expect that similar adverse impacts from exposure to conventional impact and vibratory pile driving are likely given sufficient proximity or exposure duration.

In the U.S. regulatory framework of assessing impacts of underwater sound on marine mammals, sound sources are classified as either impulsive (*e.g.*, sounds from seismic air guns or impact pile driving) or non-impulsive (*e.g.*, sounds from vessels, drilling, or vibratory pile driving) for physiological damage comprising Level A harassment (the effects taht could cause injury) [?]. The waveforms and spectrograms of DTH pile driving sound show distinctive impulsive characteristics. Although there is not a universal standard that provides a quantitative method to differentiate impulsive from non-impulsive sounds, citing Harris (1998), Southall et al. (2007) suggested using a 3 dB difference in measurements between the continuous and impulse settings of an SLM to determine whether a sound is impulsive or non-impulsive. Specifically, if the SLM measurement from the impulse setting (a 35 ms window) is 3 dB or great than the continuous setting (a 1 s window), the sound is classified as impulsive. Otherwise, it is considered non-impulsive. Denes et al. (2019) determined that the SPLs of the 35 ms pulses were 5 dB greater than those of the 1 s samples in their dataset, so they classified DTH hammering as impulsive. Similar results were evident in the measurements conducted by Reyff and Heyvaert (2019) and in our dataset (5 dB and 3.4 dB, respectively). A recent study by Martin et al. (2020) used kurtosis of a 1-min time window to examine the impulsiveness of the sound. A preliminary analysis using the kurtosis methodology confirmed that DTH pile driving sound at Thimble Shoal was impulsive (B. Martin, Pers. Comm., 12 May 2020). Therefore, all DTH pile driving sounds that we are aware of contain impulsive components.

Since DTH pile driving involves both percussive hammer strikes and drilling and debris clean-out mechanisms, the source characteristics are expected to include both impulsive and non-impulsive components. However, existing reported sound measurements regarding DTH pile driving only provided detailed analyses on the impulsive component of the sound ((Denes et al., 2019; Reyff and Heyvaert, 2019), and this study). Both Dazey et al. (2012) and Denes et al. (2016) treated DTH pile driving as only non-impulsive, continuous source by averaging the sound over a given time window in their analyses, although Denes et al. (2016) also noted the impulsive structure of the sound. The non-impulsive component of DTH pile driving sound is expected to have source characteristics similar to vibratory pile driving and drilling, which should be treated as continuous under the U.S. regulatory framework for assessing Level B harassment (the effects that could lead to behavioral disturbance, temporary avoidance, or temporary hearing threshold shift) (Scholik-Schlomer, 2015). As the impulsive (percussive hammer strikes) and non-impulsive (drilling and debris clean out) components likely exhibit vastly different sound levels, hydrophones with different sensitivities, as well as different analytical approaches, may be required to analyze adequately both components of DTH pile driving sound.

5. Conclusion

This study provides the first detailed analysis of DTH pile driving noise characteristics and near source (10 m) levels of relatively small (0.46-m diameter) steel piles in extremely shallow water (3–4 m depth). Noise characteristics for DTH pile driving include both impulsive and non-impulsive components. The impulsive component of the DTH pile driving near source (10-m) measurements showed median $L_{\mathrm{E,ss}}$ of 147 and 145 dB re 1 μPa^{2}s at 10 m for a single strike of the two piles measured. These values were lower than other DTH pile driving measurements, which were conducted in much deeper waters with larger piles (*e.g.*, (Denes et al., 2019); (Reyff and Heyvaert, 2019)). The majority of the acoustic energy from DTH pile driving were below 2 kHz. The non-impulsive component from drilling and debris clean out is expected to have source characteristics similar to vibratory pile driving and drilling and should be treated as a continuous source under the U.S. regulatory framework for assessing impacts to marine mammals (NMFS, 2018; Southall et al., 2019) and other marine species (Popper et al., 2014) from underwater noise. However, further research on noise levels and propagation characteristics of DTH pile driving for different types and sizes of piles in different environmental conditions (*e.g.*, water depth, sediment type) are needed to better understand DTH pile driving sound characteristics and their potential impacts on marine life.

CRediT authorship contribution statement

Conceptualization	Shane Guan
Methodology	Robert Miner, Shane Guan
Software	Shane Guan, Robert Miner
Validation	Robert Miner, Shane Guan
Formal analysis	Shane Guan
Investigation	Robert Miner
Resources	Robert Miner, Shane Guan
Data Curation	Shane Guan, Robert Miner
Writing - Original Draft	Shane Guan
Writing - Review & Editing	Shane Guan, Robert Miner
Visualization	Shane Guan
Supervision	Shane Guan
Project administration	Shane Guan
Funding acquisition	NA – No funding received

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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