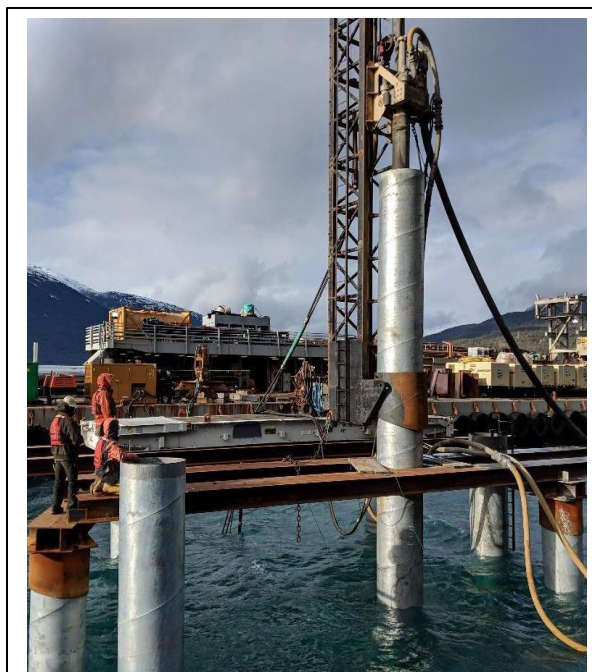




Down-the-Hole Drilling Construction Acoustic Research FINAL REPORT



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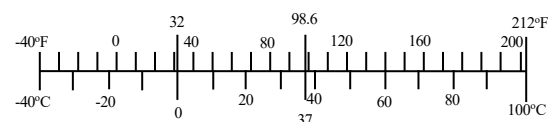
APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know Symbol	Multiply By	To Find
<u>LENGTH</u>			
in	inches	25.4	
	mm		
ft	feet	0.3048	
	m		
yd	yards	0.914	
	m		
mi	Miles (statute)	1.61	
	km		
<u>AREA</u>			
in ²	square inches	645.2	millimeters squared
	cm ² ft ²	square feet	0.0929
	meters squared	m ²	
yd ²	square yards	0.836	meters squared
	m ²		
mi ²	square miles	2.59	kilometers squared
	km ²		
ac	acres	0.4046	hectares
	ha		
<u>MASS (weight)</u>			
oz	Ounces (avdp)	28.35	grams
lb	Pounds (avdp)	0.454	kilograms
	kg T	Short tons (2000 lb)	
	0.907	megagrams mg	
<u>VOLUME</u>			
fl oz	fluid ounces (US)	29.57	milliliters
	mL gal	Gallons (liq)	
	3.785	liters	liters ft ³
	cubic feet	0.0283	meters cubed
	m ³		
yd ³	cubic yards	0.765	meters cubed
m ³ Note: Volumes greater than 1000 L shall be shown in m ³			
<u>TEMPERATURE (exact)</u>			
°F	Fahrenheit temperature	5/9 (°F-32)	Celsius temperature °C
<u>ILLUMINATION</u>			
fc	Foot-candles	10.76	lux
	lx		
fl	foot-lamberts	3.426	candela/m ²
	cd/cm ²		
<u>FORCE and PRESSURE or STRESS</u>			
lbf	pound-force	4.45	newtons
	N psi	pound-force per	
	6.89	kilopascals	kPa
	square inch		

These factors conform to the requirement of FHWA Order 5190.1A *SI is the symbol for the International System of Measurements

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply	To Find Symbol By
<u>LENGTH</u>			
mm	millimeters	0.039	inches
	in		
m	meters	3.28	feet
	ft		
m	meters	1.09	yards
	yd		
km	kilometers	0.621	Miles (statute)
	mi		
<u>AREA</u>			
mm ²	millimeters squared	0.0016	square inches
	in ² m ²	meters	squared
	10.764 square feet	ft ² km ²	kilometers squared
		0.39 square	miles
	mi ² ha	hectares (10,000 m ²)	
	2.471	acres ac	
<u>MASS (weight)</u>			
g	grams	0.0353	
	oz		
kg	kilograms	2.205	
	lb mg	megagrams (1000	kg)
	1.103	short tons T	
<u>VOLUME</u>			
mL	milliliters	0.034	fluid ounces (US)
	fl oz		
liters	liters	0.264	Gallons (liq)
	gal		
m ³	meters cubed	35.315	cubic feet
	ft ³		
m ³	meters cubed	1.308	cubic yards
	yd ³		
<u>TEMPERATURE (exact)</u>			
°C	Celsius temperature	9/5 °C+32	Fahrenheit temperature
	°F		
<u>ILLUMINATION</u>			
lx	lux	0.0929	foot-candles
	fc		
cd/cm ²	candela/m ²	0.2919	foot-lamberts
	fl		
<u>FORCE and PRESSURE or STRESS</u>			
N	newtons	0.225	pound-force
	lbf		
kPa	kilopascals	0.145	pound-force per
			psi square inch



Down-the-Hole Drilling Construction Acoustic Research

Southeast Alaska

December 2024

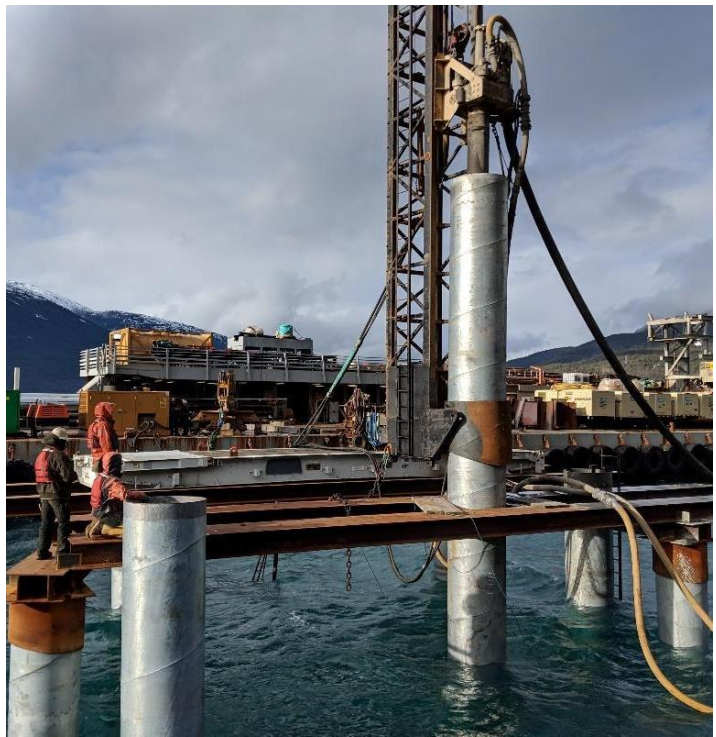


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Common Terms for DTH Underwater Sounds

Acoustic Parameter	Description	Equivalent Terms
Lp,pk	Peak sound pressure, maximum pressure from 0 to peak	Peak
Lp,rms	Root mean square (rms) sound pressure level with an undefined time energy window	RMS, SPL
Lp,rms,90%	Root mean square (rms) sound pressure level with 90% energy window	RMSss, RMSpulse Pulsed SPL
Lp,rms,1s	Root mean square (rms) sound pressure level with 1-second energy window	RMS, RMScont, SPL
LE,ss	Sound exposure level for a single DTH pulse	SEL, SELss
LE,cum	Cumulative sound exposure level for a DTH event or day	Cumulative SEL SELcum

Term	Description
DTH	Down the Hole, a common method used to drill holes through hard or rock substrates.
DTH Driving	DTH that utilizes a pneumatic hammer to drill a hole while advancing a casing or pile at the same time.
DTH Drilling	DTH that utilizes a pneumatic hammer to drill a hole below a casing/pile or without a casing or pile without advancing a casing or pile at the same time.
Rock socket	A drilled hole using DTH techniques to support a casing or pile
Rock tension anchor	High tensile strength bars or strands installed in DTH drilled holes in the rock stratum that are tensioned to a specified load to counteract uplifting forces. For purposes of this report these tension anchors secure installed piles.

EXECUTIVE SUMMARY

This report examines underwater sound measurements reported for projects involving down-the-hole (DTH) drilling techniques. At the time this report was prepared, there were 12 projects identified that included measurements. Results of these measurements were examined and summarized in this report. The purpose was to establish the best available database of DTH acoustic data to use in describing DTH sounds for biological assessments for Endangered Species Act consultations and preparation of marine mammal incidental harassment applications under the Marine Mammal Protection Act.

DTH sounds were found to fall under two distinct types of activities, as described by Guan et. al. (2022): DTH driving, where the pile or casing advances with the drilled hole, and DTH drilling, where the hole is drilled below the pile or casing. DTH driving sounds are louder than DTH drilling sounds and more impulsive. DTH sounds appear to fall off at a greater rate with distance than that of impact and vibratory pile driving sounds. The acoustic frequency content of DTH sounds were examined and compared to weighting factors applied for marine mammal hearing.

Sound levels and representative frequency weighting adjustments were identified for different pile or casing sizes that involve DTH driving techniques. Sound levels and frequency weighting adjustments were developed that apply to DTH drilling activities. Recommended sound levels propagation rates and driving/drilling times are provided in Tables ES-1 and ES-2.

Table ES-1. Recommended DTH system levels at 10 meters from pile/casing*

Pile/Hole diameter	LE,ss dB re: 1μPa ² sec	Lp,rms, 90% dB re: 1μPa	Lp,pk dB re: 1μPa	Lp,rms,1s dB re: 1μPa	TL ** (Level A)	TL** (Level B ₁)
DTH Drilling						
all sizes <33-inches	145 dB	161 dB	172 dB	155 dB	18.3	18.3
DTH Driving						
9 to 18 inches	146 dB	162 dB	172 dB	158 dB	15	18.6
19 to 24 inches	156 dB	173 dB	184 dB	167 dB	15	18.6
25 to 30 inches	162 dB	178 dB	192 dB	174 dB	15	18.6
25 to 42 inches	164 dB	180 dB	192 dB	174 dB	15	15.6
>42 inches	No data available					

* These levels are for activities involving single DTH operations.

** TL = Transmission loss.

It is important to note that actual transmission loss depends on a number of environmental factors and can vary significantly from location to location. Therefore, applying estimations of transmission loss from one location to another should be done with caution and should consider the relative differences of the two environments. The source characteristics are also an important factor, and it is possible that for this source the transmission loss may be characteristically different than other types of pile driving/drilling.

Frequency adjustments to compute the onset of auditory injury (AUD INJ) were identified based on frequency spectra or power spectral density data reported. This report found substantial differences in adjustments for high-frequency (HF) cetaceans and both Phocid and Otariid phocids,

when compared to default values used in the National Marine Fisheries Services (NMFS) User Spreadsheet.

Table ES-2. Comparison of DTH system weighted frequency adjustments

Activity	Frequency WFAs (at 10 m) in dB re: 1 μ Pa ² sec				
	Cetaceans			Pinnipeds	
	LF	HF	VHF	Phocid	Otariid
DTH Driving (average*)	-1	-13	-24	-9	-15
DTH Drilling (average*)	-1	-11	-26	-7	-14
NMFS User Spreadsheet default (2.0 kHz)	-0.03	-3.45	-21.19	-0.80	-5.23

*These WFAs are the average of measurements, where there is considerable variation.

The DTH hammer frequency was found to be 13 to 14 hertz (Hz) for DTH driving of piles/casings 30 inches in diameter or smaller and 8 Hz (7 to 10 Hz) for larger piles. DTH drilling had a much higher hammer frequency rate of 20 Hz (15 to 22 Hz).

The duration to conduct this DTH activities ranged from about 540 to 6,300 seconds for DTH driving and 900 to 4,000 seconds for DTH drilling. Hammering rates were on the order of 8 to 14 Hz for DTH driving and 20 Hz for DTH drilling of rock tension anchors (small diameter holes). Generally, larger diameter holes had lower hammering rates.

INTRODUCTION

The Alaska Department of Transportation and Public Facilities (DOT&PF) is conducting research regarding down-the-hole (DTH) drilling in noise underwater conditions. This report describes the currently available studies of underwater sound measurements for DTH drilling and driving along with a description of the fundamentals of DTH activities and current acoustic thresholds.

Projects that DOT&PF designs and constructs in the Southeast Alaska marine environment may involve DTH drilling methods due to the hard rock surfaces to be encountered at various depths. Many of these projects require an Incidental Harassment Authorization (IHA) under the Marine Mammal Protection Act and Consultation under Section 7 of the Endangered Species Act. These processes are lengthy and typically require DOT&PF to provide information on anticipated sound source levels and how they propagate during construction. This information is necessary to estimate take numbers of marine mammals and identify shutdown and monitoring zones for assessing potential injury and behavioral impacts on marine mammals (i.e., Level A and Level B harassment). There is a rich presence of marine mammal life within Southeast Alaska waters, and so predicting accurate underwater sound impacts is essential to protect these resources during construction of vital public projects.

Many marine projects involve pile installation using vibratory drivers/extractors¹ and/or impact pile driving. Underwater sounds from these activities have been well documented in publications, for example, there are compendiums prepared by Caltrans (2020), and the U.S. Navy (2015 and 2016), along with many project-specific compliance reports submitted to resource agencies. However, there are limited acoustical data available for DTH activities as the first published measurements were made available in 2016 (Denes et al. 2016). DOT&PF is currently active in pursuing additional data. In addition, the National Marine Fisheries Services (NMFS) recognizes the acoustical issues with DTH sounds and is encouraging the collection and dissemination of additional sound data.

In 2016, DOT&PF conducted a hydroacoustic pile driving noise study which is useful for describing in-water pile driving noise impacts, however, it did not specifically address DTH drilling installation (Denes et al. 2016). DTH drilling techniques have become increasingly common with marine projects in Southeast Alaska. This method can be used to install rock sockets or rock tension anchors into a drilled hole within a pile into underlying bedrock after the pile has been driven through overlying sediments to refusal. Rock socket drilling involves drilling down through substrate consisting of boulders and rock with a drill bit equipped with a DTH hammer. The sounds throughout this operation cycle includes various levels of drilling with intermittent hammering and clean-out of the pile socket. Rock tension anchor drilling involves setting a casing using a pneumatic air hammer, then a rock anchor drill bit with a DTH hammer operates within the casing. The rock anchor holes are substantially smaller in diameter and deeper than the rock sockets and there is less interaction between the drill and the casing or pile; therefore, result in a much lower sound. The sound source is located where hammering occurs well within the substrate. Sounds from this activity include hammering of the casing, drilling and intermittent rock hammering, and cleanout of the hole. Like rock-socket drilling, sounds from this operation vary through cycles of drilling with intermittent hammering and clean-out of the hole. Intermittent and continuous hammering occurs for both rock sockets and tension anchors. (Reyff and Heyvaert 2019). Intermittent hammering typically occurs at the beginning where the substrate is softer.

To date there have been about a dozen studies that measured DTH drilling for rock sockets and tension anchors within the United States, in part because rock casing and tension anchor installation was previously not considered a substantial noise source until about 2020. As a result, NMFS's current recommendations are based on limited available data and are likely conservative when defining ensonified areas that can cause hearing and/or behavioral impacts to marine mammals.

DOWN-THE-HOLE DRILLING

Down-the-hole (DTH) drilling is a common method used to drill holes through hard or rock substrates. A pneumatic DTH hammer is driven by pressured air coming from an air compressor that provides the energy to power the percussion piston that hits the drill bit with a specific impact frequency and energy to break the rock (Brito et. al. 2023). The compressed air also flows through

¹ A vibratory driver/extractor is a machine that grips a pile and vibrates it up and down. When the vibrating pile is pushed into the ground, soil around the pile begins to vibrate and breaks the friction between the pile and the soil, thus allowing it to penetrate the ground.

the drill bit, performing hole cleaning by removing the debris outside the drilled hole. DTH uses rotary cutting percussion action using a button bit. In DTH drilling, the percussion mechanism, or hammer, is located directly above the drill bit. The drill pipe transmits the necessary feed force and rotation to the hammer and bit, along with the compressed air used to actuate the hammer and flush the cuttings. The primary sound components are impulsive sounds from percussive hammering and continuous sounds from the rotary drill action and the release of compressed air. With the use of a DTH drill for rock socketing, the casing used for the drilling operations is larger than the production pile since the hole drilled is intended to be large enough to seat the production pile. Figure 1 shows a DTH hammer fitted with a button bit that was used to drill rock casings for 30-inch vertical piles during construction of the Gravina Freight Facility.

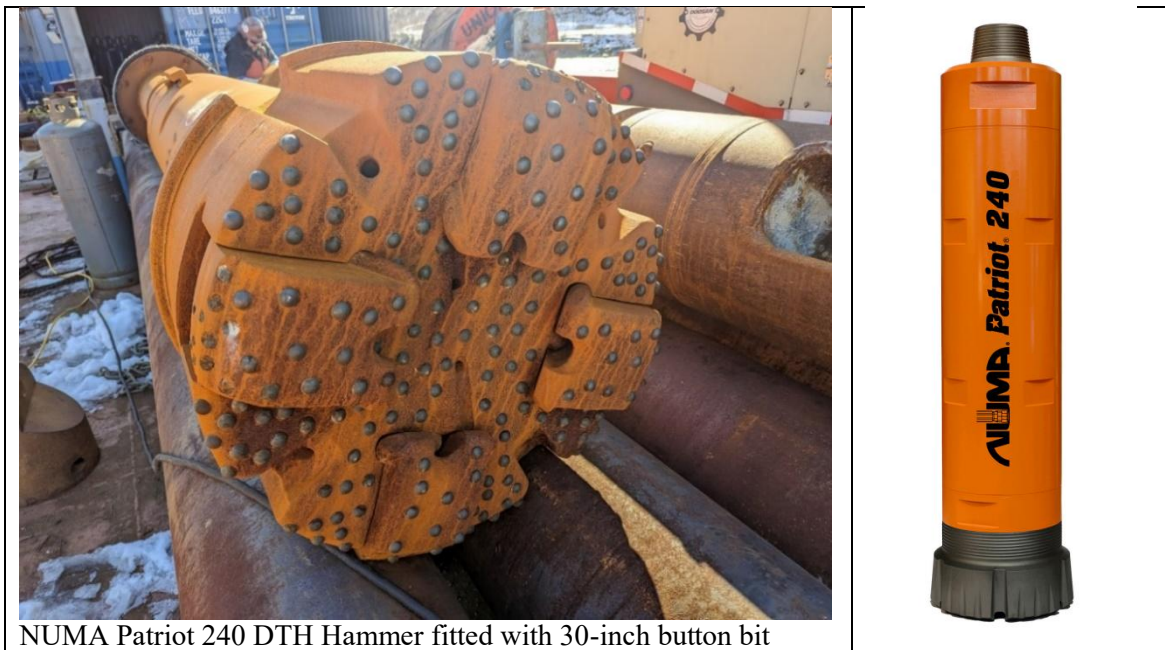


Figure 1. NUMA Patriot DTH hammer



Figure 2. DTH drilling of a 24-inch diameter dolphin pile

Guan et al. 2022 makes a distinction between DTH pile drilling (Figure 2) and DTH pile driving, where the hammer does not make contact with the pile for DTH drilling but does for DTH driving. Figure 3 shows DTH pile driving where the DTH hammer directly strikes the steel pile shoe. Additionally, recent measurements for DTH driving (Reyff and Ambaskar. 2023) have shown that when the DTH hammer is within the casing, it can contact the walls of the casing and cause elevated sound levels. This was an example of an ‘upset’ condition. There are two types of DTH operations that have been most common:

Rock Sockets: Drilled holes through overburden material and into rock stratum for steel pipe piles. This construction method utilizes DTH pile driving.

Rock Tension Anchors: High tensile strength bars or strands installed in drilled holes in the rock stratum that are tensioned to a specified load to counteract uplifting forces. This construction method is considered DTH drilling, even though a percussive drill is used. However, there is no pile or casing within the drilled holes that could make direct contact with the DTH drilling equipment.

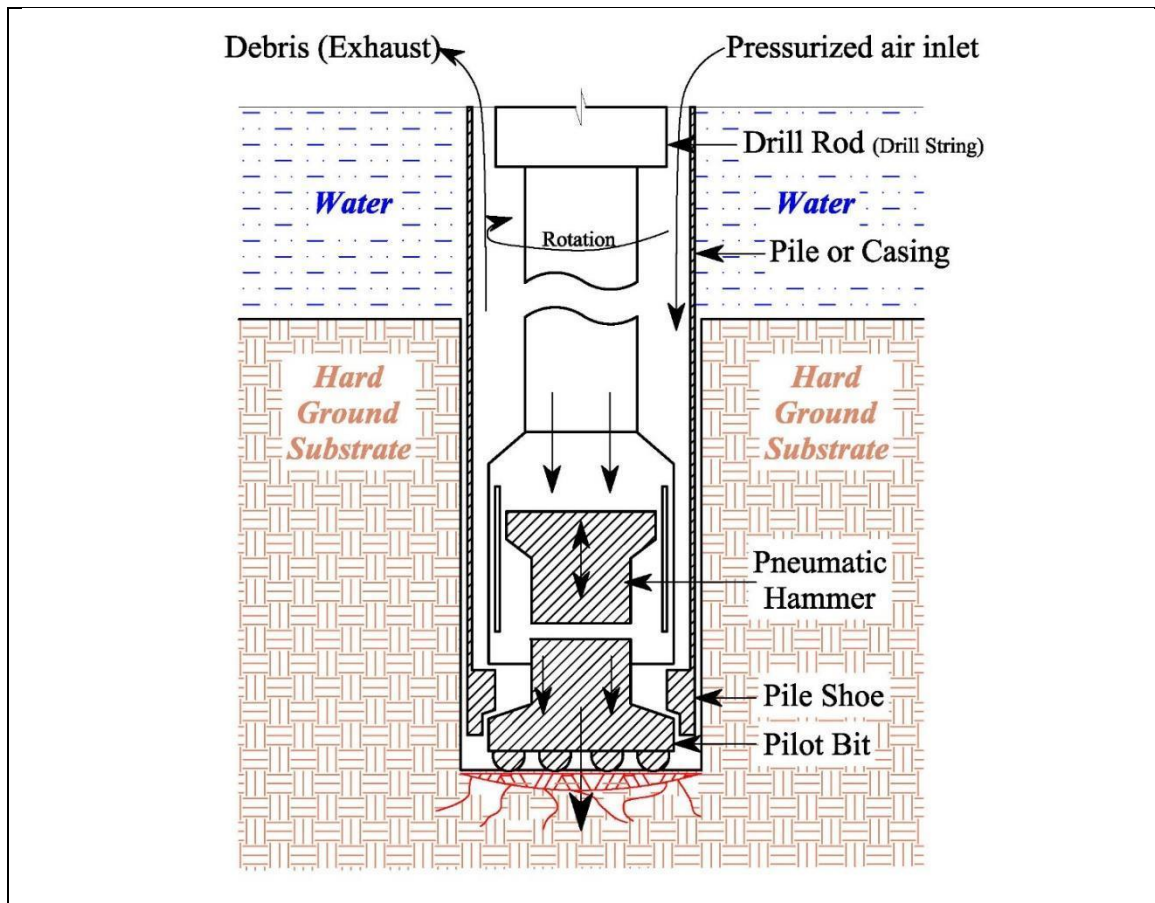


Figure 3. Schematic diagram of DTH pile driving (with pile)

Figure 4a shows an example of rock socket DTH pile driving, where the rock socket is created with the casing or pile in place. Figure 4b shows rock tension anchor pile drilling where the rock anchor is drilled beneath the pile.

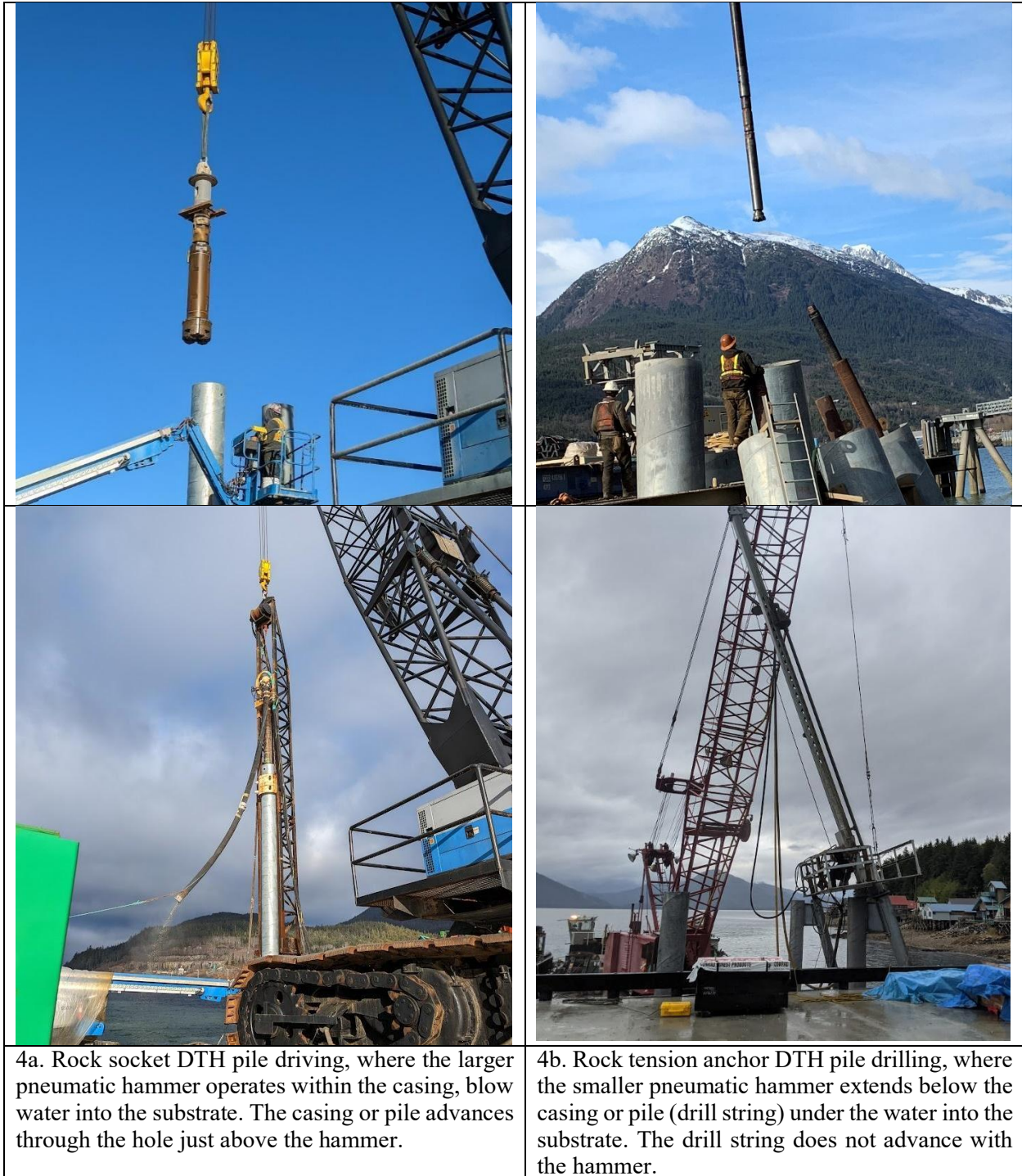


Figure 4. Rock socket DTH pile driving (4a) and rock tension anchor DTH pile drilling (4b)

Vertical pile installation using DTH typically follows these steps:

1. Position and drive production pile/casing down to bedrock through vibratory driving. An impact hammer may be used to seat the pile/casing after vibratory driving.

2. Insert the drill-string with drill bit inside the production pile/casing. Note that a slightly smaller diameter hole is drilled.
3. Attach rigging to the top of drill string and clear out the overburden material inside the pile/casing until bedrock using compressed air.
4. Once the drill bit locks into place beneath the pile/casing, rock-socketing procedure with percussive drilling begins (note that the percussive action is meant to occur below the pile/casing tip). This is the stage where the DTH hammer may contact the pile, thus generating louder sounds.
5. Once DTH tip elevation is achieved, the rigging equipment and drill string are removed.
6. An impact hammer may be briefly used to secure the pile into bedrock (i.e., until refusal).

ACOUSTIC FUNDAMENTALS AND TERMINOLOGY

Sound is defined as small disturbances in a fluid (liquid or gas) from ambient conditions through which energy is transferred away from a source by progressive fluctuations of pressure (sound waves). Sound waves are produced by vibrating objects. For the purposes of this document, the vibrating object is a pile that has been excited by the percussive drilling. The resulting sound can be produced impulsively (impact), continuously (vibration) or a combination of both impulsive and non-impulsive methods that occurs with DTH drilling.

Acoustic Terms

Various acoustical terms are used in this report. Definitions of acoustic terms (ISO 18405:2017) are provided below, while a more comprehensive list is provided in *Appendix A*.

Sound pressure is the instantaneous absolute positive or negative pressure and is presented in this report as a decibel referenced as 1 micropascal (dB re 1 μ Pa). While several acoustical metrics are used to describe sounds in the environment, the root-mean-square (RMS) sound pressure level is an appropriate descriptor to describe measured sounds from continuous and impulsive sounds but with different averaging time constants. The RMS sound pressure level is presented in dB re: 1 μ Pa and is averaged over a defined time period in a stated frequency range or band. The appropriate time period to average for the RMS computation varies by the type of sound (e.g., impulsive or non-impulsive). The steady sound pressure level which, over a given period of time, has the same total energy as the actual fluctuating noise is often referred to as the L_{eq} (equivalent continuous sound level). Thus, the L_{eq} is in fact the RMS sound level with the measurement duration used as the averaging time. Sound Exposure Level (SEL) is proportionally equivalent to the time integral of the pressure squared and is described in this report in terms of dB re: 1 μ Pa² sec over the duration of a sound event. The Peak sound pressure is the largest absolute value of the instantaneous sound pressure. Sounds for DTH pile installation are typically measured over the frequency range of 20 to 20,000 hertz (Hz). These acoustic metrics have the following definitions as applied to this purpose:

Decibel and Reference Pressure

Underwater sounds can be expressed in several different physical quantities, such as acoustic energy (joules), power (watts), intensity (watts per unit area), and pressure (pascals or micropascals). The most common method in which underwater sounds are expressed is in terms

of a relative unit of decibels (dB). This is a logarithmic ratio of a physical quantity to a reference quantity, in this case sound pressure. The decibel used to describe sound is expressed in the following equation:

$$SPL = 10 \log_{10} \left(\frac{p}{p_0} \right)^2 \quad (1)$$

where SPL is the sound pressure level, p is the root-mean-square (RMS) acoustic pressure, and p_0 is the reference acoustic pressure: $p_0 = 1 \mu Pa$ in water and $p_0 = 20 \mu Pa$ in air². Typically, a sound pressure level is mentioned in terms of dB re 20 μPa or dB re 1 μPa where ‘re’ is shorthand for the term ‘in reference to’. Sound Pressure Levels (SPLs) from installing piles depend on many factors, such as amplitude, frequency, and impulsiveness. Several sound level metrics are used to evaluate the effects of underwater sounds on marine life such as peak sound pressure level, RMS sound pressure levels, sound exposure level (SEL), and more.

All decibels reported are referenced to 1 μPa for peak pressures and RMS (or L_{eq}) levels. SEL is reported in dB referenced to 1 μPa^2 sec.

Peak Sound Pressure Level

For this application, the maximum or absolute highest value of the measured sound pressure expressed in dB re 1 μPa is the peak sound pressure level (sometimes referred to as zero to peak pressure). Impulsive pile driving events are characterized by the maximum and median Peak sound pressure level per strike (of all strikes).

$$Lp_{pk} = 20 \text{Log} \left(\frac{p_{pk}}{p_0} \right)^2 \quad (2)$$

Where

Lp_{pk} is the peak sound pressure level expressed in dB,
 p_{pk} is the measured peak pressure in μPa , and
 p_0 is the reference pressure of 1 μPa .

Peak sound pressure level is used to assess a potential auditory injury (AUD INJ) and a temporary threshold shift (TTS) in the hearing of marine mammals, gastrointestinal tract injury in marine mammals, and mortality and injury in fish and sea turtles exposed to impulsive sound.

SEL – Sound Exposure Level

The total sound exposure during a measured event expressed in dB re 1 μPa^2 sec. The events used to describe the sounds are individual DTH pulses (or pile strikes), expressed as LE_{ss} , and pile installation activities that are made up of all pile sounds, expressed as LE_{cum} . DTH pile installation events are characterized by the arithmetic median LE_{ss} (of all pulses or strikes) and the LE_{cum} for the entire pile driving event.

² Note that sounds expressed in dB with a reference pressure of 1 μPa would differ from those typically expressed in air with a reference pressure of 1 μPa by +26 dB (Caltrans 2020).

$$LE, ss = 10 \log_{10} \left[\frac{1}{T_0} \int_{t_0}^{t_{100}} \frac{p^2(t)}{p_0^2} dt \right] \quad (3)$$

Where

LE, ss is the SEL for an event expressed in dB,
 T_0 is a referenced time interval³,
 t_0 is the beginning of the duration of the time series,
 t_{100} is the entire (100%) duration of the time series,
 $p(t)$ is the time varying acoustic pressure in a waveform in μPa , and
 p_0 is the reference pressure of 1 μPa .

LE, ss for DTH events is typically described for each impulse and LE, cum for the total event. The SEL for the total event or all events in one day is also commonly referred to as the cumulative sound exposure level or Daily LE, cum . Daily LE, cum is used to assess potential AUD INJ and TTS in marine mammals and sea turtles when exposed to impulsive or non-impulsive sounds. A 12-hour exposure window is used to evaluate the mortality or injury of fish exposed to impulsive sound.

In an evaluation of impulsive sound impacts, it is necessary to estimate the cumulative SEL (LE, cum) associated with the number of daily pulses that accumulate. This can be directly measured or estimated from a representative single-strike SEL value and the number of pulses that occur to place a pile at the final depth by using the following equation:

$$LE, cum = LE, ss + 10 \log_{10}(\# \text{ of pulses}) \quad (4)$$

This equation provides a reasonable estimate of cumulative SEL, given a representative single pulse SEL value and an accurate representation of the number of pulses.

RMS – Root-Mean-Square Sound Pressure Level

The RMS SPL is the method used to describe the energy of a sampled waveform in terms of sound pressure expressed in dB referenced to 1 μPa . This is defined mathematically as the square root of the mean value of the squared pressures taken over an interval. For individual pile pulses (or strikes), the RMS SPL is measured over the period of time that energy in the sampled waveform for an impact is between 5 percent and 95 percent of the total sampled energy. This is also referred to as $L_{p,rms}$ in later sections of this report.

$$L_{p,rms} = 10 \left[\frac{1}{T} \int_{t_{05}}^{t_{95}} \frac{p^2(t)}{p_0^2} dt \right] \quad (5)$$

Where

$L_{p,rms}$ is the RMS SPL for an impulse expressed in dB,
 t_{05} and t_{95} make up the time duration in seconds, where t_{05} corresponds to the time that 5% of the energy has accumulated from an impulse and t_{95} is when 95% of the energy has accumulated,

³ For impact pile driving, a 1-sec referenced time interval is used. For DTH installations, the inter-pulse interval is much less than 1-sec.

p is the measured pressure in micro pascals (μPa), and
 p_0 is the reference pressure of 1 μPa .

For continuous sounds, the equation is the same, but the time period (or time constant) used to measure RMS SPL is one second. This is referred to as $L_{p,rms,1s}$ in later sections of the report. Pile installation events are characterized by the median $L_{p,rms,90\%}$ per strike (of all pulses or strikes) or all seconds.

$L_{p,rms,90\%}$ is used to assess potential behavioral disturbance in marine mammals from impulsive sound exposure, measured over 90% of the acoustic energy, and continuous RMS for non-impulsive sound exposure. It is important to note that for non-impulsive or continuous sounds, $L_{p,rms,1s}$ is the RMS SPL in a 1-sec duration. This would have the same value as the calculated SEL in 1-sec for continuous and non-impulsive sounds.

Sound Types

For assessing underwater sound effects in terms of AUD INJ or TTS on marine mammals, NMFS groups sounds into two categories: Impulsive or Non-Impulsive. NMFS considers sounds such as impact pile driving, blasting, and seismic surveys as impulsive. Other sounds such as drilling and vibratory driving are considered non-impulsive. DTH drilling sounds contain both impulsive and non-impulsive aspects. Sounds that propagate into the acoustic far field become less impulsive with increased distance. Harris 1998 (as referenced by Southall et al 2007) suggests that if the sound level meter measurement of the construction activity using the impulse setting (a 35ms time window) is 3-dB or more than the measured level using the continuous setting (a 1s window), the sound is classified as impulsive. This definition has been used to define impulsive sounds for DTH measurements (Denes et. al. 2019, Guan et. al. 2022, Reyff and Ambaskar 2023).

Distinct sounds that last less than one second, such as acoustic pulses from impact driving strikes, are typically impulsive. DTH drilling with a percussive bit produces impulsive sound near the source. In other words, the percussive hammer striking makes the sound impulsive. As sound propagates away from the source and blends into background, the sounds become less impulsive. The distance at which this occurs is dependent on the amplitude of the impulsive sound, amplitude of the continuous components, and characteristics of the background sound level. Additionally, sounds from the debris pumping operations that are carried out when the DTH hammer is engaged result in non-impulsive sounds. At greater distances, contribution of background sound and acoustic propagation effects reduce the impulsivity of the DTH sounds received at far distances. Therefore, sounds from DTH activities could be considered both impulsive and continuous.

Figure 5 shows a time history snapshot of impulsive DTH sounds with time in seconds on the x-axis and sound pressure signal in terms of Volts/dB on the y-axis. In this example, the percussive DTH drilling rate is 14 Hz. Typically, larger diameter piles have lower percussive rates of about 10 to 15 Hz, while smaller diameter piles or casings can have higher rates in excess of 20 Hz. The higher rates are accompanied by lower amplitude sounds.

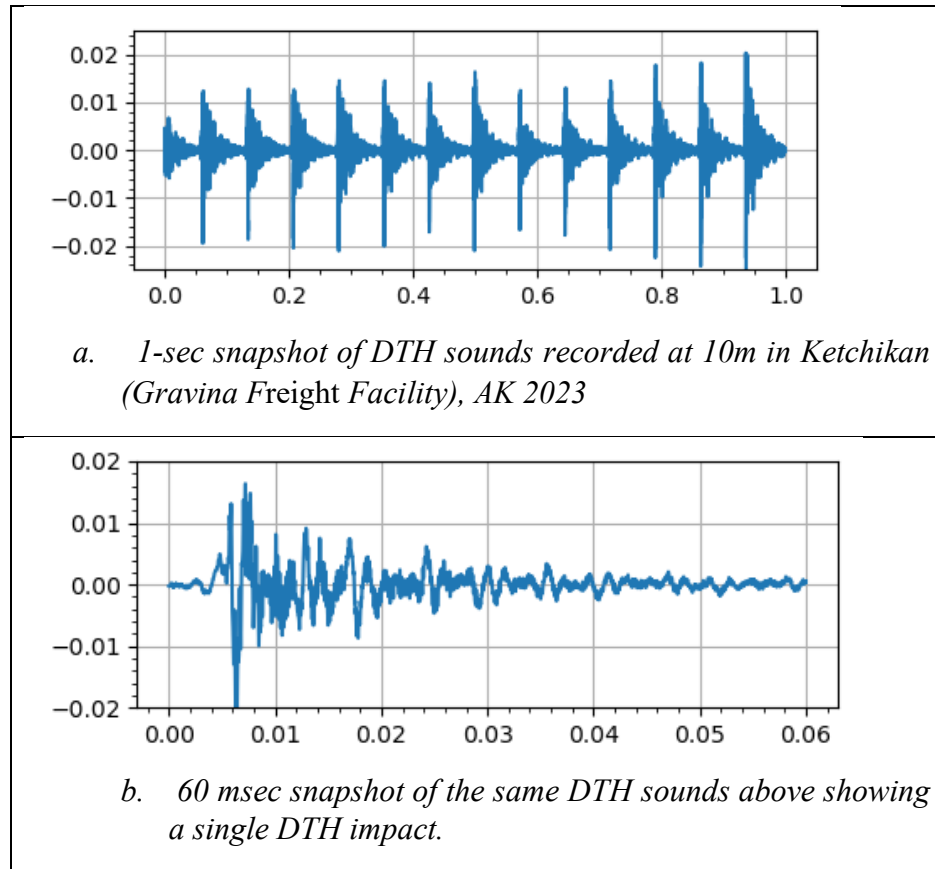


Figure 5. Time history snapshot of impulsive DTH sounds with time in seconds on the x-axis and sound pressure in Volts/dB on the y-axis [Source: Reyff and Ambaskar 2023]

Sound Frequency (Hz)

Underwater sounds consist of a range of frequencies. This is referred to as the ‘frequency spectrum’ of the sound. Frequency is measured in cycles per second or Hz. Sounds from underwater construction are typically described over a range of frequencies (bandwidth). The bandwidth can either be as narrow as 1 Hz or as wide as 1/3rd octave or one octave. An octave corresponds to a doubling of frequency. The importance of the frequency spectra of underwater sounds lies in the fact that the frequency content of the sound may affect the way fish and marine mammals respond to and are affected by the sound in terms of a temporary effect or a permanent injury. The frequency content of sounds from underwater construction could potentially affect communication among fish and among marine mammals.

1/3rd Octave Band Analysis (1/3rd OBA)

Octave bands are the interval between one pitch and another with double its frequency. Fractional octave bands such as 1/3rd of an octave is widely used in engineering acoustics to describe the frequency content (or pitch) of measured sounds. A ‘1/3rd octave band plot’ provides another commonly used method to visualize how a sound source is distributed over the frequency spectrum in terms of a ‘1/3rd octave’ bandwidth. Figure 6 illustrates both the power spectral density (PSD) and 1/3rd octave band spectrum for DTH sounds.

PSD – Power-Spectral-Density

PSD is the measure of a sound signal's power content versus frequency in one-Hz bands. A PSD is typically used to characterize broadband signals. The amplitude of the PSD is normalized by the spectral resolution employed to digitize the signal. For acoustic data, a PSD has amplitude units in dB per Hz referenced to $\mu\text{Pa}^2/\text{Hz}$. Figure 6 includes a PSD plot (1-Hz narrow bandwidth resolution) for a single DTH pulse superimposed with the median PSD for the entire duration of the DTH pile driving, and a 1/3rd-octave band plot. The points that comprise the 1/3rd-octave band plot are made up of the sum of narrow band sound levels in that frequency range.

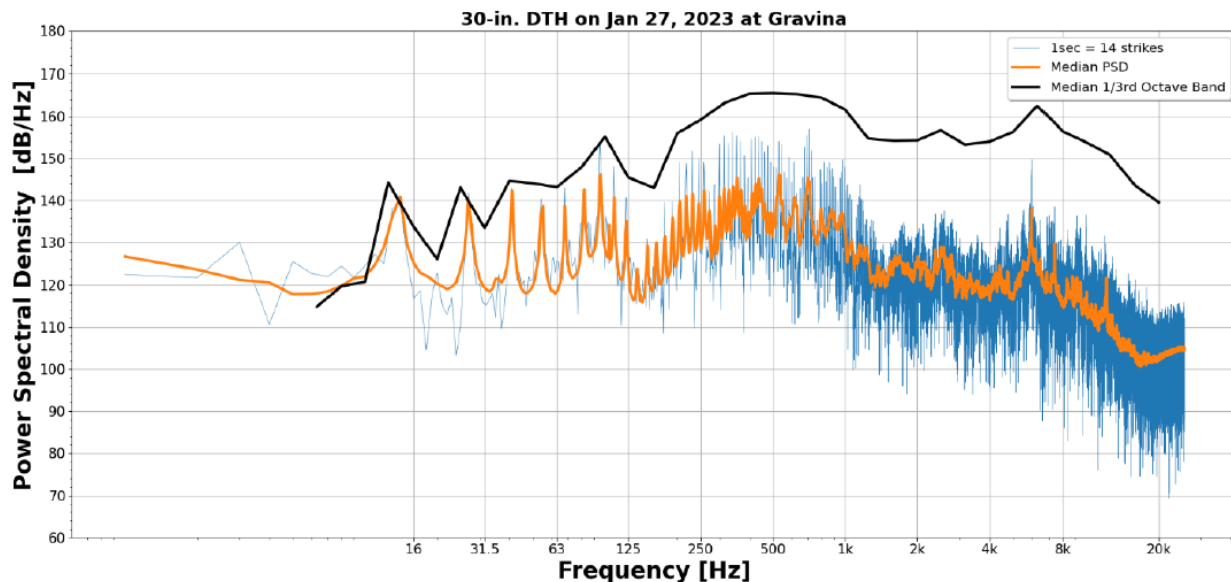


Figure 6. Power Spectral Density for DTH sounds in dB per Hz with 1/3rd octave band spectra in dB superimposed [Source: Reyff and Ambaskar 2023]

As discussed previously, the frequency content of the sound source is important in the context of evaluating effects on fishes and marine mammals. Auditory weighting functions are applied to sound sources to evaluate how sounds affect different groups of marine mammals as per the Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing provided by NMFS (2018). At the time of this report preparation (fall 2024), NMFS was in the process of updating the 2018 technical guidance (NMFS 2024). Table 1 defines the different marine mammal hearing groups based on their hearing range, as recently proposed by NMFS.

Table 1. Definition of Marine Mammal Hearing Groups

Functional Hearing Group	Generalized Hearing Range*
Low-frequency (LF) Cetaceans – baleen whales	7 Hz to 36 kHz
High-frequency (HF) Cetaceans – dolphins, toothed whales, beaked whales, bottlenose whales	150 Hz to 160 kHz
Very high-frequency (VHF) Cetaceans – true porpoises, <i>kogia</i> , river dolphins, <i>Cephalorhynchus</i> , <i>Lagenorhynchus cruciger</i> & <i>L. australis</i>	200 Hz to 160 kHz
Phocid Pinnipeds (PW) – true seals, including harbor seals	40 Hz to 90 kHz
Otariid Pinnipeds (OW) – sea lions and fur seals	60 Hz to 68 kHz

* Represents the generalized hearing range for the entire group as a composite (i.e., all species within the group), where individual species' hearing ranges are typically not as broad. Generalized hearing range chosen based on ~65

dB threshold from normalized composite audiogram, with the exception for lower limits for LF cetaceans (Southall et. al. 2007) and PW pinniped (approximation). [Source: NMFS 2024]

WFA – Weighting Factor Adjustments

NMFS Guidance (2018) defined frequency dependent marine mammal auditory weighting functions (WFAs) that reflect hearing or susceptibility to noise-induced hearing loss. At the time of this report preparation (fall 2024), NMFS was in the process of updating the 2018 technical guidance (NMFS 2024). Figures 7 and 8 show the WFAs proposed in 2024 by NMFS for the different groups of marine mammals shown in Table 1 above.

WFAs developed by NMFS are used in their optional User Spreadsheet tool to incorporate the NMFS Technical Guidance’s full (i.e., over the entire frequency band associated with the sound source) marine mammal auditory weighting functions (NMFS 2020). Auditory weighting functions take into account what is known about marine mammal hearing sensitivity and susceptibility to noise-induced hearing loss and can be applied to a sound-level measurement to account for frequency-dependent hearing (Southall et al. 2007). This is an expression of relative loudness as perceived by the ear. WFA’s are incorporated by a function representing a specified frequency-dependent characteristic of hearing sensitivity in a particular animal group, by which the sound level in a particular frequency is adjusted to reflect the importance of that frequency to that animal. Marine mammal auditory weighting functions reflect the risk of noise exposure on hearing and do not necessarily capture the most sensitive hearing range of every member of the hearing group. Source-specific frequency spectrum data could be used to override the WFA, which is based on a single frequency.

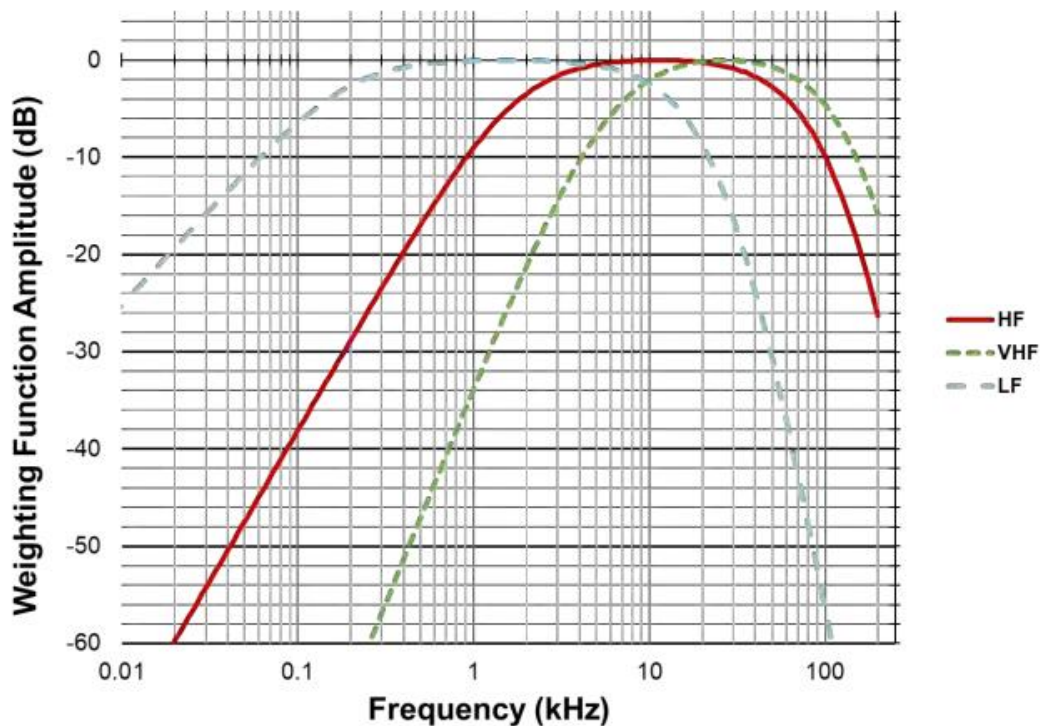


Figure 7. Auditory weighting functions for low, mid, and high frequency cetaceans (NMFS 2024)

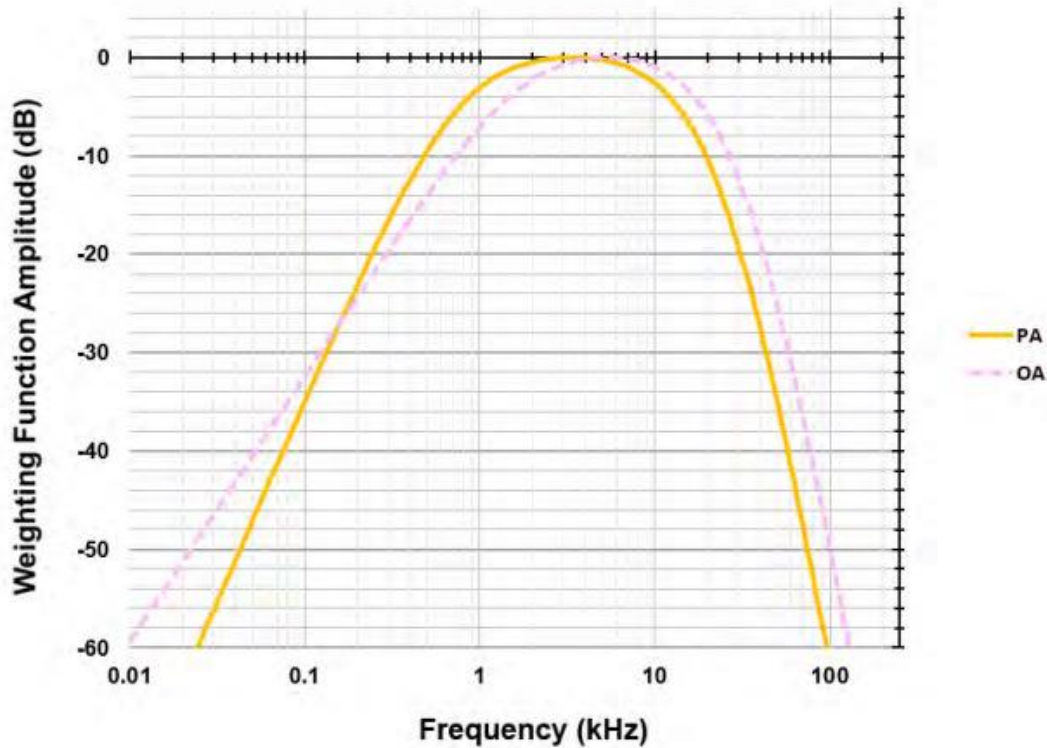


Figure 8. Auditory weighting functions for otariid and phocid pinnipeds (NMFS 2024)

Sound Transmission Loss

Transmission Loss (TL) is the decrease in a sound metric as an acoustic pressure wave propagates out from a source. The reduction in sound levels as they propagate out from a source may result from a combination of geometric spreading, energy loss to the medium through which the sound propagates, and complex interaction with non-uniformities in the medium transmitting or reflecting the propagating sound. An example of a DTH sound propagating away from a DTH source is illustrated in Figure 9. The simplest form of calculating TL is shown below; however, some forms of TL computations include frequency dependent effects.

$$TL = B \log_{10} \left(\frac{R_1}{R_2} \right) \quad (6)$$

Where

TL is the difference in sound, in dB, measured at two distances,

B is a transmission loss coefficient, typically expressed as the sound loss per 10-fold change in distance,

R_1 is the distance between the point of model interest and the sound source, and

R_2 is the distance between the sound source and the point of assumed source level.

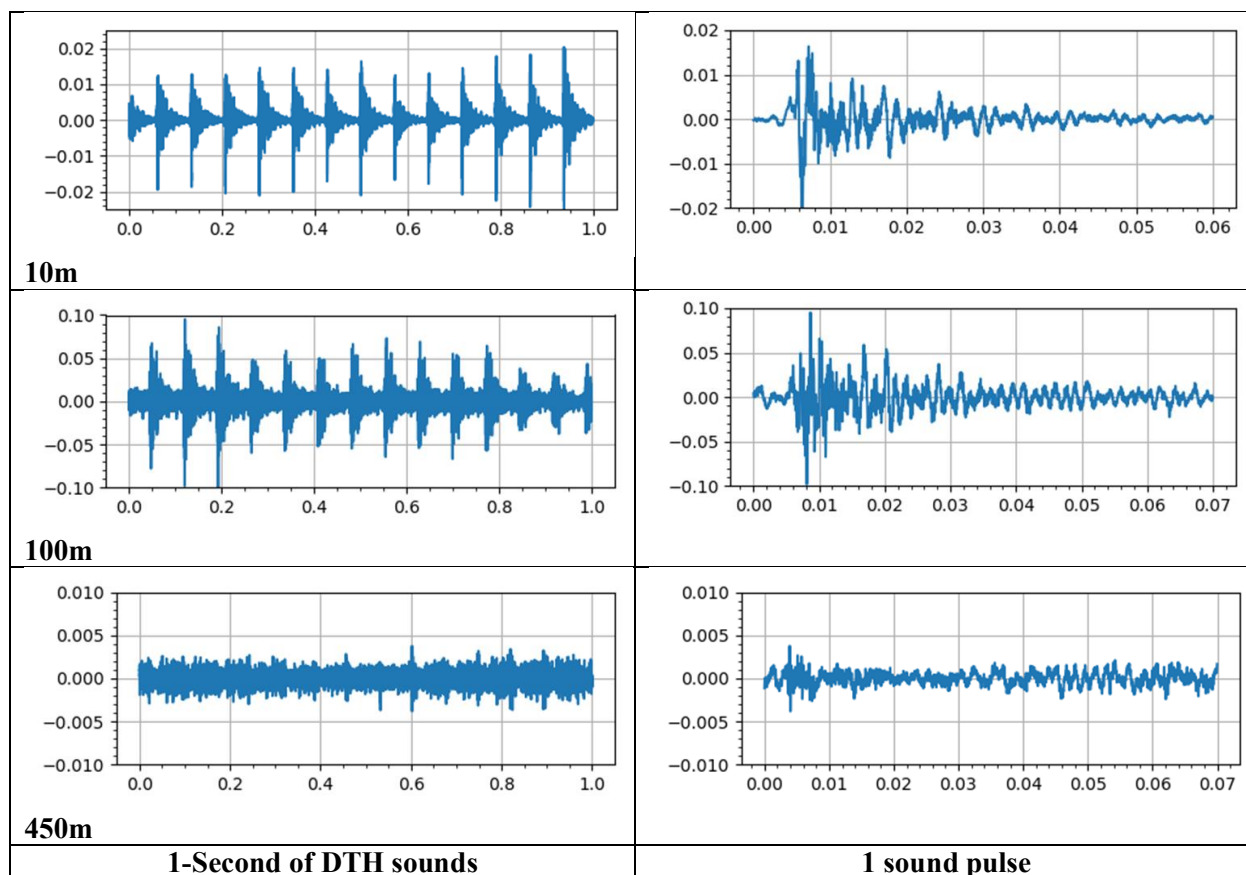


Figure 9. Example of attenuated acoustic waveforms for 30-in. diameter pile DTH pulses at various distances with time in seconds on the x-axis and sound pressure in volts on the y-axis [Source: Reyff and Ambaskar 2023]

CURRENT ACOUSTIC THRESHOLDS

Sound exposure thresholds have been developed for various aquatic organisms that include marine mammals, fish, and sea turtles. Since sea turtles are not present in Alaskan waters, these thresholds are not discussed in this report.

Marine Mammal Thresholds

Under the Marine Mammal Protection Act, NMFS has defined levels of harassment for marine mammals. Level A harassment is defined as “Any act of pursuit, torment, or annoyance which has the potential to injure a marine mammal or marine mammal stock in the wild.” Level B harassment is defined as “Any act of pursuit, torment, or annoyance which has the potential to disturb a marine mammal or marine mammal stock in the wild by causing disruption of behavioral patterns, including but not limited to migration, breathing, nursing, breeding, feeding, or sheltering.”

NMFS has provided marine mammal acoustic technical guidance for predicting onset of TTS and AUD INJ, which includes, but is not limited to, permanent threshold shifts (PTS) in marine mammal hearing from sound sources. Onset of AUD INJ is considered Level A harassment of marine mammals. Table 2 below outlines the currently adopted Level A and Level B (behavioral

harassment) criteria. The application of the threshold for continuous sounds can sometimes be problematic because this threshold level can be near or below the ambient noise level at certain locations. For continuous sounds, NMFS Northwest Region (2012) has provided guidance for reporting RMS sound pressure levels. RMS levels are typically based on the median level for sounds using a time-constant of all 1- or 10-second RMS values (e.g., $L_{p,rms,1s}$). For impulses, the overall RMS level should be characterized by integrating sound for each acoustic pulse across 90 percent of the acoustic energy in each pulse and reporting the median of all the $L_{p,rms,90\%}$ for all pulses (see Acoustic Terms section).

Impulsive sounds correspond to those that are typically transient, brief (typically less than 1 second), broadband, and consist of high peak sound pressure with rapid rise time and decay. Non-impulsive sounds are those that could be broadband, narrowband or tonal, brief or prolonged, continuous or intermittent, and usually do not have a high peak sound pressure with rapid rise and decay times (NMFS 2018). The latest NMFS guidance (NMFS 2022) recommends the following acoustic thresholds to assess sounds from DTH systems.

- Level A harassment: Impulsive thresholds by marine mammal hearing group (both cumulative sound exposure level, LE_{cum} , and peak sound pressure level, $L_{p,pk}$; NMFS 2024).
- Level B harassment: Continuous RMS threshold (i.e., RMS sound pressure level, e.g., $L_{p,rms,1s}$, 120 dB). Note that the application of the 120-dB RMS SPL threshold can be adjusted in certain circumstances to the ambient level in louder environments⁴.

NMFS uses behavior thresholds rather than TTS thresholds for assessing Level B harassment for pile driving and DTH systems. NMFS recently updated the 2018 technical guidance (NMFS 2024). The guidance was peer reviewed by experts and then reviewed by the public. No comments that would result in substantial changes to the guidance were received. Table 2 provides the current guidance that includes thresholds for the onset of AUD INJ that are based on the 2024 guidance.

Table 2. Adopted Underwater Acoustic Criteria for Marine Mammals

Species	Underwater Noise Thresholds				
	RMS SPL and Peak are expressed in dB re: 1 μ Pa and SEL in dB re: 1 μ Pa ² sec				
	Continuous sounds Disturbance Threshold (<i>Level B Harassment</i>)	Intermittent sounds Disturbance Threshold (<i>Level B Harassment</i>)	Marine Mammal Hearing Group (see Table 6)	AUD INJ Onset Threshold	
				Impulsive	Non-Impulsive
Cetaceans	120 dB RMS*	160 dB RMS*	Low Frequency	222 dB $L_{p,pk}$ 183 dB LE_{cum}	197 dB LE_{cum}
			High Frequency	230 dB $L_{p,pk}$ 193 dB LE_{cum}	201 dB LE_{cum}
			Very High Frequency	202 dB $L_{p,pk}$ 159 dB LE_{cum}	181 dB LE_{cum}

⁴ This is practice for projects that include representative acoustical measurements that are reported and approved by NMFS.

Pinnipeds	120 dB RMS*	160 dB RMS*	Phocid	223 dB Lp,pk 183 dB LE _{cum}	195 dB LE _{cum}
			Otariid	230 dB Lp,pk 185 dB LE _{cum}	199 dB LE _{cum}

*Typically assessed using the arithmetic median of the Lp,rms,1s

Regulators typically estimate noise induced impacts to fish and marine mammals based on classifying anthropogenic sound into either impulsive or non-impulsive sounds. However, sounds from DTH construction activities are more complex involving both impulsive and non-impulsive components due to percussive pile striking and debris removal. Guan (2022) reported the use of kurtosis values to quantify the impulsiveness of DTH sounds for different marine mammal groups and developed adjusted marine mammal AUD INJ thresholds specific to DTH sounds. These kurtosis values were developed using audiometric data derived from human and terrestrial mammals, which may not reflect marine mammal hearing physiology and auditory effects from complex sound exposures. There are currently no regulatory thresholds that are based on kurtosis values. NMFS recognizes that additional or more appropriate metrics, such as kurtosis, may be identified in the future. However, additional research would be required to understand the relationship to marine mammal hearing and the practicality of measuring and applying metrics (NMFS 2024).

Fish Thresholds

In 2008, the National Oceanic and Atmospheric Administration's (NOAA) NMFS, U.S. Fish and Wildlife Service, California, Oregon, and Washington Departments of Transportation; California Department of Fish and Game; and the U.S. Federal Highway Administration agreed in principle to interim criteria to protect fish from impulsive pile-driving activities. The agreed-upon criteria are presented in Table 3.

The adopted criteria listed in Table 3 are for pulse-type sounds (e.g., impact pile driving) and do not address sounds from vibratory driving (non-impulsive sounds). The LE_{cum} criteria are not applied to vibratory driving sounds. The in-water areas with project sound levels above 150 dB RMS are considered by NMFS to be acoustically affected, resulting in possible behavioral changes in fish; however, these levels are not anticipated to trigger any mitigation requirements (Caltrans 2020). Note that sounds below 150 dB LE_{ss} are not considered to cause injurious impacts to fish, as this level is considered effective quiet.

Table 3. Interim Fish Criteria for Impulsive Pile Driving

Interim Criteria for Injury	Sound Levels Agreed-upon in Principle
-----------------------------	---------------------------------------

Peak, Lp,pk	206 dB re 1 μ Pa (for all sizes of fish)
Cumulative SEL, LE _{cum}	187 dB re 1 μ Pa ² -sec – for fish size of 2 grams or greater* 183 dB re 1 μ Pa ² -sec – for fish size of less than 2 grams*

* Applies to pile strikes of 150 dB SEL (single strike) or greater.

Following the establishment of interim acoustic criteria, several studies both in the lab and field were conducted to better understand the effects of pile driving noise on fish. These are described in Popper et al. (2014). Popper et al. (2014, 2019) developed sound guidelines for fish that focused on fish groups, based on fish hearing type, sound source, and major potential effects that were based on a critical review of all available studies, including more recent studies and advancements in the understanding of the interaction of fishes with the acoustical environment. Table 4 lists the lowest levels recommended where injury was found, and the onset of TTS is predicted.

Table 4. Sound Guidelines for Fish Presented as Sound Pressure

Fish Hearing Group	Onset of Mortality		Recoverable Injury		TTS
	LE _{cum}	Lp,pk	LE _{cum}	Lp,pk	LE _{cum}
Fishes without swim bladder	>219	>213	>216	>213	>186
Fishes with swim bladder not involved in hearing	210	>207	203	>207	>186
Fishes with swim bladder involved in hearing	207	>207	203	>207	186
Eggs and larvae	>210	>207			

[Source: Popper et al. 2014]

The updated report (Popper et al. 2019) synthesizes the available literature on effects of noise exposure and proposes groups of fishes with different types of swim bladders, as well as eggs and larvae, which are expected to vary in their specific physical, physiological, and behavioral responses to exposure to noise. These experts indicate that:

- Fishes with no swim bladder or other gas chamber (e.g., flatfishes) detect only particle motion, not sound pressure, for hearing; these fish may not suffer auditory injury and are less susceptible to barotrauma injury, although some barotrauma may result from exposure to sound pressure.
- Fishes with swim bladders not involved in hearing (e.g., Pacific salmon) are susceptible to barotrauma injury from exposure to high-energy SPLs but may not suffer auditory injury since hearing involves only particle motion, not sound pressure.
- Fishes with swim bladders or other gas volume that are involved with hearing (e.g., cod, walleye pollock) detect sound pressure as well as particle motion; these fish are susceptible to both barotrauma injury and auditory injury from exposure to high SPLs.

The 2014 Interim Guidelines (Popper et al. 2014) are based on multiple injuries, rather than sound levels that may result in the onset of a single injury. Popper et al. (2019) strongly suggest that the 2008 Interim Criteria are excessively conservative and that the sound levels for significant impacts to fish should be higher than those specified in the 2008 Interim Criteria. As of this date, the sound guidelines for fish recommended by Popper et.al. (2019) have not been adopted by NMFS. In general, the recommended guidelines indicate higher SEL thresholds than the interim fish criteria.

NMFS ACOUSTIC GUIDANCE FOR ASSESSMENT OF DTH SYSTEMS

NMFS provided the following guidance for assessing sound impacts from DTH systems (NMFS 2022):

Level A Assessment

Until new data become available (or site-specific sound data for the proposed source that have been reviewed and deemed acceptable by NMFS), NMFS recommends the following levels (referenced 10 m from source) using the LE_{ss} and Lp,pk be used for assessing Level A harassment:

Table 5. NMFS Level A Recommended DTH System Levels*

Pile/Hole diameter	LE_{ss} (at 10 m)	Lp,pk (at 10 m)	Reference
8 inches and smaller	144 dB	170 dB	Reyff 2020
9 to 18 inches	146 dB	172 dB	Guan & Miner 2020
19 to 24 inches	159 dB	184 dB	Hayvaert & Reyff 2021
25 to 42 inches	164 dB	194 dB	Denes et al. 2019; Reyff & Heyvaert 2021; Reyff 2020
>42 inches	No measurements are currently available. Applicants are to contact NMFS for recommended levels.		

* These levels are for activities involving single DTH operations.

Frequency content is an important aspect of the Level A thresholds. The NMFS User Spreadsheet includes a specific tab for DTH systems (i.e., Tab E.2). For DTH systems, a WFA of 2 kHz should be assumed, unless more complete spectral data are available. Based on the Draft 2024 updated guidance, a 2-kHz WFA results in the sound level adjustments for each marine mammal group that are shown in Table 6.

Table 6. WFAs Applied to DTH Systems in dB

Functional Hearing Group	DTH Systems 2-kHz Cutoff (dB)
Low Frequency Cetaceans (LFC)	0.0
Mid Frequency Cetaceans (HFC)	-3.45
High Frequency Cetaceans (VHFC)	-21.19
Phocid pinnipeds (PW)	-0.8
Otariid pinnipeds (OW)	-5.2

Other inputs to the spreadsheet include the source levels (along with their distance), shown above in Table 5, strike rate, duration, number of piles or holes, and transmission loss. For coastal activities, if area-specific information on propagation/transmission loss is not available, NMFS typically recommends practical spreading function of the distance (See Equation 6, where $B = 15$).

Level B Assessment

NMFS (2022) recommends RMS SPLs that are based on continuous levels (e.g., $L_{p,rms,1s}$), as shown in Table 7.

Table 7. NMFS Level B Recommended DTH System Levels

Pile/Hole diameter	$L_{p,rms,1s}$ (at 10 m)	Reference
8 inches and smaller	156 dB	Reyff 2020
9 to 24 inches	167 dB	Guan & Miner 2020
25 to 42 inches	174 dB	Reyff & Heyvaert 2019; Reyff 2020
>42 inches	No measurements are currently available. Please contact NMFS for recommended levels.	

DTH HYDROACOUSTIC STUDIES

This section contains acoustical information on underwater sound measurements resulting from DTH activities conducted in southeast Alaska, Virginia, and New Hampshire. Of the 12 studies identified, there were 11 identified studies that involved the measurement of underwater sound from DTH systems. These studies have been reviewed to identify acoustical content with respect to characterizing underwater sound from DTH systems. DTH sounds are described in terms of rock socket driving and rock tension anchor drilling. As the presented data demonstrate, rock socket driving generates considerably higher sound levels than rock tension anchor sounds.

Summary of Sound Levels

There is a fairly large variation in underwater sound levels based on the relatively small sample size of studies that are available. Unlike previous findings for pile driving, there does not appear to be a clear relationship between pile/casing/hole size and sound level. There appears to be a relationship between size and sound level only when all data from rock socket DTH pile driving are combined with those for DTH drilling (e.g., rock tension anchors). Recent research has shown that these two methods have different sound generating mechanisms, and therefore, it would be inappropriate to combine these datasets. Instead, the results of these studies were separated into the two categories: DTH Rock Socket Driving and DTH Rock Drilling.

Note that near-source underwater sound levels for pile driving measurements have been standardized to 10 m from the pile being driven (Caltrans 2020)⁵. While the mechanisms for generating sound from pile driving are complex, extending from the pile tip up through the pile, this distance provides sound levels that are useful for describing source levels. DTH driving or drilling mechanisms are more complex as the source of sound is mainly where the percussive hammer strikes the hard substrates beneath the pile and water, while also interacting with the pile and or pile shoe. In some cases, this is well below the water column. However, this varies with many of the projects reviewed. Therefore, the close-in reference distances of 10 m from the pile used for DTH activities may not be appropriate and be a source of the large variation in levels for piles of similar size. Based on the data collected, sound levels are still normalized to 10 m from the pile. Table 8 summarizes sound levels that occur at 10 m from the pile. The summary data are

⁵ The range of 10 m is chosen because there have been a large number of measurements already made at this range by researchers, allowing for a degree of comparison in results.

based on the weighted average (by sample size) of assigned values for each type of DTH activity measured. Typically, the assigned level is the average of representative levels reported (or calculated) at 10 m from the DTH pile/casing. Unusual events were not included in computing the assigned values.

Table 8. Summary of Measured DTH Sound Levels

Pile/Casing Diameter in inches	Number of Samples	Avg. Median $L_{p,rms_{1s}}$	Avg. Median LE_{ss}	Avg. Median $L_{p,rms_{90\%}}$	Avg. Median $L_{p,pk}$	Avg. Rate (Hz)	Avg. TL*
DTH Driving							
18	2	158	146	162	172	13	--
24	15	167	156	173	184	13	18.6
30	2	174	162	178	192	14	19.7
42	8	173	164	180	191	8	15.6
DTH Drilling							
8-10	15	155	145	161	172	20	18.9
33	2	149	140	153	161	12	14.3

* Not all studies provided adequate data to compute a TL.

DTH Rock Socket Driving

There were seven studies that involved rock socket driving that used DTH drilled holes to support piles or casings. The range of hole diameters was approximately 18 to 42 inches. Each project is described below.

18-inch Diameter – Biorka Island

DTH pile driving measurements were conducted at Symonds Bay at a U.S. government facility on Biorka Island near Sitka, in southeastern Alaska (Guan and Miner 2020). Sound levels were measured from various pile installations that included vibratory driving and DTH driving of 18-inch diameter open-end steel pipe piles. Table 9 summarizes sound levels measured for this project.

- **Type of Piles Driven and Type of DTH Hammer Used:** Two events of DTH activities were measured, one for each pile (F14 and E14). The piles installed were approximately 15 m long and 0.46 m (18 in.) in diameter open-end steel pipe piles. The DTH hammer used was a Patriot® 125 hammer manufactured by Numa.
- **Water Depths and Measurement Locations:** The water depth at the pile, and at the 10 m location was approximately 3 to 4 m. At the 200-m and 1200-m locations, the water depth was approximately 7 to 9 m, and 15 m deep, respectively.
- **Duration of DTH Driving or Drilling:** DTH pile driving of the F14 took approximately 62 minutes, which included 21,742 hammer strikes. DTH pile driving of E14 took approximately 109 minutes with 38,631 hammer strikes on August 15.
- **Locations from the Pile Where the Measurements Were Made:** Measurements were made at approximately 10, 200, and 1200 m from the pile. However, most hammer strikes were not detected at a distance of 1,200 m and were hence excluded from further analysis.

- **Strike Rate of the DTH Hammer Used:** The DTH hammer strikes at a rate of 10 to 14 strikes per second.
- **Background or Ambient Measurements Made:** Background or ambient sound levels were about 110 to 130 dB. Background noise appeared to be elevated by the onset of heavy swells.
- **Transmission Loss (TL):** Specific transmission loss was not computed from measurements since levels at 1,200 m could not be clearly detected.
- **Frequency Spectrum:** Sounds from DTH activities were predominantly low frequency, spanning from about 100 to 1,000 Hz. Since the measurement analysis was based on evaluation of single strikes, the fundamental hammer frequency at about 12 Hz is not revealed.

Table 9. Summary of 18-in. Biorka Island DTH Driving Measurements

Pile Id	Distance (m)	Lp,rms _{1s}	LE _{ss}	Lp,rms _{90%}	Lp,pk	Rate (Hz)	Duration (sec)	TL
F14	10	NR	147	162	173	13	3,720	NR
	200	NR	127	140	148			
E14	10	NR	145	161	170	13	6,540	NR
Assigned Value	10	158	146	162	172	13	--	--
WFA Adjustment (dB)								
Pile ID	LFC	HFC	VHFC	PW	OW			
Computed at 10m	-2.8	-21.8	-31.5	-15.4	-24.3			

NR = not reported.

24-inch Diameter - Kodiak Study

This study included DTH pile driving sound measurements at the Kodiak ferry terminal in southern Alaska (Denes et al., 2016). Rock sockets were drilled, and the piles were set in the sockets with a vibratory hammer. The drilling was necessary due to the seabed composition at Kodiak, which consisted of a thin sediment layer overlying bedrock. The sediment layer did not provide enough structural support on its own, necessitating the creation of pile sockets in the bedrock. Table 10 summarizes the DTH sound levels measured for this project.

- **Type of Piles Driven and Type of DTH Hammer Used:** At Kodiak, there were eight DTH pile driving activities measured that involved drilling into bedrock to create sockets for setting 24-inch diameter steel piles, each were 69 feet long with a 0.5-inch wall thickness. Impulsive sounds were not measured for this study; however, the single strike SEL is computed based on dividing the 1-second SEL by the number of pulses (strike rate).
- **Measurement Locations:** Measurements were taken from two locations: one close to the piles (approximately 10 to 30 m away) to capture near-field sound characteristics and another approximately 1.1 kilometer away for computing transmission loss.
- **Water Depths:** Water depth was about 5 m near the piles driven and 15 m deep away from the pile.
- **Duration of Drilling Events:** Duration of drilling ranged from 40 minutes to 4 hours per pile, depending on specific conditions encountered with each pile.
- **Strike Rate of DTH Hammer:** The DTH hammer used for drilling had a strike rate of approximately 15.5 Hz (about once every 66 milliseconds).

- **Background Noise Levels:** Background sound levels were measured at 100 dB, based on the median level of measured RMS values.
- **Transmission Loss (TL):** The computed TL coefficient for DTH driving was 18.9 dB/decade ($B=18.9$).
- **Frequency Spectrum:** Sounds from DTH activities were predominantly low frequency, spanning from about 200 to 2,000 Hz. The frequency plot revealed the fundamental hammer frequency at 15.5 Hz, highlighting the acoustic signature of the drilling process.

Table 10. Summary of 24-in. Kodiak DTH Driving Measurements

Pile Id	Distance (m)	Lp,rms _{1s}	LE _{ss}	Lp,rms _{90%}	Lp,pk	Rate (Hz)	Duration (sec)	TL
D22	10	146.5	NR	NR	NR	NR	13,163	NR
	1,117	114.8					13,185	
D20	13	168.9	NR	NR	NR	NR	3,215	NR
	1,119	131.8					3,219	
D18	16	167.0	NR	NR	NR	NR	2,766	NR
	1,122	130.8					2,767	
D16	19	161.3	NR	NR	NR	NR	2,711	NR
	1,125	127.5					2,713	
D15	22	151.9	NR	NR	NR	NR	3,924	NR
	1,127	126.9					3,929	
D14	25	148.4	NR	NR	NR	NR	4,075	NR
	1,130	123.4					4,082	
D13	28	152.5	NR	NR	NR	NR	2,890	NR
	1,133	124.6					2,894	
D12	31	153.0	NR	NR	NR	NR	3,161	NR
	1,136	124.8					3,167	
Reported Value	10	166	NR	NR	NR	15.5	NR	18.9
Assigned Value	10	166	154*	--	--	15.5	--	18.9
WFA Adjustment**								
Pile ID	LFC	HFC	VHFC	PW	OW			
Computed at 10m	-0.3	-10.6	-23.3	-5.5	-13.0			

NR = not reported.

* Computed based on the strike rate of 15.5 pulses per second.

** WFA based on computed average for all piles except D22. The authors reported WFAs that were based on the original 2016 guidance. WFAs were recomputed from spectra data.

24-inch Diameter – Tenakee Springs SSV

This study measured sounds from DTH pile driving of rock sockets and DTH pile drilling of rock tension anchors that were part of improvements made for the Tenakee Springs Ferry Terminal in southeastern Alaska (Heyvaert and Reyff 2021). The rock sockets measured were part of pile installation that constructed the new bridge support float. DTH driving was conducted for rock sockets. Measurements of rock tension anchor DTH drilling was conducted for the bridge support float piles. Table 11 summarizes the DTH sound levels measured for this project.

- **Type of Piles Driven and Type of DTH Hammer Used:** The DTH driving for four rock sockets to accommodate 24-inch diameter steel pipe piles were measured.
- **Locations where the Measurements Conducted:** Measurements were made at approximately 10 m (near position), 100 to 200 m (middle position), and about 1,000 m (distant position). Roving measurements were also made.
- **Water Depths:** The water depths for the pile installations varied, depending on the tide and distance from shore, ranging from approximately 3 to 6 m deep near the pile to over 50 m away from the piles.
- **Duration of DTH Driving or Drilling:** The DTH driving activities lasted about 2,640 to 3,600 seconds for each event.

- **Strike Rate of the DTH Hammer Used:** The DTH hammer used for rock socket driving had a strike rate of approximately 9 Hz (9 strikes per second).
- **Background or Ambient Measurements:** Overall ambient median RMS sound levels were measured at 118 dB near the activity and 104 dB at the distant position.
- **Transmission Loss (TL):** The TL was reported to be between 19.1 and 20.3, depending on the various sound metrics such as $L_{p,rms1s}$, $L_{p,pk}$, $L_{p,rms90\%}$, and LE_{ss} .
- **Frequency Spectrum or PSD of the Measured Sounds:** Measured sound levels were greatest over 80 to 2,500 Hz at the near position, with less low frequency sound at further distances.

Table 11. Summary of 24-in. Tenakee Springs DTH Driving Measurements

Pile Id	Distance (m)	$L_{p,rms1s}$	LE_{ss}	$L_{p,rms90\%}$	$L_{p,pk}$	Rate (Hz)	Duration (sec)	TL
R-4	12	164	154	169	183	9	~1,180	NR
	188	146	136	150	163			
	974	127	117	129	143			
R-3	10	164	154	169	183	9	~1,460	NR
	194	146	136	154	163			
	980	128	118	134	129			
R-2	12	164	154	173	183	9	~1,500	NR
	210	146	136	151	160			
	990	128	118	139	135			
R-1	8	167	157	173	182	9	~1,540	NR
	210	148	138	153	163			
	990	127	117	130	144			
Assigned Value	10	167	159	173	184	9	1,500	19.1
WFA Adjustment								
	LFC	HFC	VHFC	PW	OW			
All	-1.9	-16.6	-21.5	-6.4	-6.6			
At 10m	-2.9	-9.4	-16.9	-7.7	-10.0			

24-inch Diameter – Metlakatla Seaplane Facility Refurbishment Project

DTH driving sound measurements were made during reconstruction of the Metlakatla Seaplane Facility in Metlakatla Harbor on Annette Island, in southeastern Alaska (Miner 2023). DTH driving sounds were measured for the installation of three 24-inch diameter steel piles through rock sockets. The driving of one pile had to be terminated soon after beginning, so only partial data were measured. Therefore, these measurements are not considered in this dataset. The evaluation of these data is based on the two piles that were fully installed. Table 12 summarizes the DTH sound levels measured for this project.

- **Type of Piles Driven and Type of DTH Hammer Used:** The piles driven were 24-inch diameter piles. A "Ring Bit" DTH hammer manufactured by Robit, PLC, was used for driving/drilling. This setup included a ring-bit at the bottom of the pile for percussive drilling and a pilot bit that engaged the ring-bit to drill into the rock.
- **Locations from the Pile where Measurements Conducted:** Measurements were made at 10 m, approximately 1,000 m, a distance referred to as "3H" (3 times water depth, which varied between 30 to 37 m from the pile), an intermediate range of 140-150 m, at roving distances of 135 to 525 m, and a fixed position 1,000 m from the pile driving activities.

Note that measurements at roving positions were not considered in this study when computing the TL coefficient.

- **Water Depths:** The piles were installed in water depths ranging from approximately 10 to 14 m. The foundation design called for a rock socket depth of 6.1 m.
- **Duration of DTH Driving or Drilling:** The drilling duration varied slightly per pile, but were about one hour or 3,600 seconds.
- **Strike Rate of the DTH Hammer Used:** The apparent average hammer strike rate was approximately 9.2 to 11.0 strikes per second (10 Hz average), computed from the total number of strikes and the total driving time for those strikes on different days.
- **Background or Ambient Measurements:** The background median RMS sound level without construction was measured at 108 dB near the project area and 106 dB near the ~1,000-m measurement position at Hub Rock.
- **Transmission Loss (TL):** Transmission Loss coefficients computed for the various acoustic descriptors were 14.4 to 17.4 dB/decade.
- **Frequency Spectrum:** Most of the sound energy lies between 25 Hz and approximately 1 kHz, with little energy present above 3 kHz.

Table 12. Summary of 24-in. Metlakatla DTH Driving Measurements*

Pile Id	Distance (m)	Lp,rms _{1s}	LE _{ss}	Lp,rms _{90%}	Lp,pk	Rate (Hz)	Duration (sec)	TL
Pile 1	10	170	160	174	186	11	~3,400	14.2***
	37	160	150	164	177			
	150	147**	137	150	164			
	1,000	142**	132	145	159			
Pile 2	10	163**	153	166	180	9	~3,600	17.7***
	31	151	142	156	168			
	142	139**	129	142	154			
	1,000	127**	117	131	141			
Assigned Value	10	165	155	169	180	10	3,500	15.5
WFA Adjustment								
Pile ID	LFC	HFC	VHFC	PW	OW			
Assigned at 10m	-1.4	-14.1	-27.5	-9.0	-16.4			

NR = not reported.

* Data from roving positions not included.

** Computed based on reported pulse rate.

*** Includes roving measurements that were only made for partial periods of driving period.

24-inch Diameter – Gravina Freight Facility SSV

DTH driving sound measurements were made during construction of the Gravina Freight Facility near Ketchikan Alaska (Reyff and Ambaskar 2023). This facility included mooring dolphins comprised of 30- and 24-inch diameter piles supported using rock sockets constructed using DTH methods. The first 24-inch diameter pile driven had an upset condition where the pilot bit was caught inside the casing, causing more noise, and requiring substantial more time to drill the socket. These data were not included in the analysis of 24-inch diameter DTH pile driving. Table 13 summarizes the DTH sound levels measured for this project.

- **Type of Piles Driven and Type of DTH Hammer Used:** Two 24-inch diameter piles were installed in rock sockets. The DTH hammer used was a NUMA Patriot 240 with approximately 23-inch diameter button bits. Impact driving was conducted to seat the piles
- **Locations from the Pile where Measurements Conducted:** Measurements were made at a range of 10 m, 110 to 115 m, 500 to 610 m, and 910 to 1,140 m away from the pile.
- **Water Depths:** The piles were installed in water depths ranging from approximately 15 to 17 m with similar or deeper water at the far measurement positions.
- **Duration of DTH Driving or Drilling:** The duration for driving these piles was about 4,300 seconds for the first pile that had driving issues and about 550 seconds for the second pile.
- **Strike Rate of the DTH Hammer:** Pulses for the 24-inch piles occurred at a rate of 14 Hz.
- **Ambient Sound Measurements:** The ambient sound levels measured to the south of the project site in Tongass Narrows were between 110 to 116 dB during daytime hours, based on median RMS sound levels measured over 3 days. Note that levels in at other portions of the Tongass Narrows were louder due to vessel activity and wharf noise (ship maintenance in Ketchikan).
- **Transmission Loss (TL):** The TL coefficient was reported to be between 19.4 and 21.8 for various metrics.
- **Frequency Spectrum:** The majority of sound content occurred below 1,000 Hz, with signatures of the hammer rate generally from 14 to 80 Hz.

Table 13. Summary of 24-in. Gravina DTH Driving Measurements

Pile Id	Distance (m)	Lp,rms _{1s}	LE _{ss}	Lp,rms _{90%}	Lp,pk	Rate (Hz)	Duration (sec)	TL
S3	10	178	166	181	196	14	~4,300	NR
	10	180	169	183	195			
	110	165	154	167	181			
	115	162	150	163	177			
	500	146	134	146	159			
	910	140	128	140	150			
S2	10	172	161	175	186	14	~540	NR
	10	173	162	176	187			
	100	160	149	162	173			
	110	162	151	164	176			
	610	136	125	137	146			
	1140	133	121	134	143			
Assigned Value	10	175	164	178	190	14	540	19.4
WFA Adjustment								
	LFC	HFC	VHFC	PW	OW			
S2 all positions	-1.3	-25.0	-29.0	-10.3	-10.1			
S2 at 10m	-1.3	-14.0	-26.6	-8.6	-16.4			

NR = not reported.

30-inch Diameter – Gravina Freight Facility SSV

Construction of the Gravina Freight Facility near Ketchikan, AK, also included two 30-inch diameter piles that made up the outer mooring dolphin (Reyff and Ambaskar 2023). These were

also installed using DTH driving in the same manner as the 24-inch piles discussed previously. Table 14 summarizes the DTH sound levels measured for this project.

- **Type of Piles Driven and Type of DTH Hammer Used:** Measurements for the two 30-inch diameter piles using DTH driving techniques were conducted. The DTH hammer used was a NUMA Patriot 240 with approximately 29-inch diameter button bits for the 30-inch diameter piles.
- **Locations from the Pile where the Measurements were Made:** Measurements for the 30-inch piles were conducted at distances from about 10 m out to 975 m.
- **Water Depths:** The water depth for the 30-inch pile installations was between 15 to 18 m with similar or deeper water at the further measurement positions.
- **Duration of DTH Driving or Drilling:** The driving event lasted similar times for both 30-inch piles, approximately 1750 seconds or 24,500 pulses.
- **Strike Rate of the DTH Hammer Used:** The strike rate was 14 Hz.
- **Ambient Sound Measurements:** The ambient sound levels measured south of the project site in Tongass Narrows were between 110 to 116 dB during daytime hours, based on median RMS sound levels measured over 3 days.
- **Transmission Loss (TL):** The TL coefficient was reported to be between 19.7 and 23 for various metrics.
- **Frequency Spectrum:** The sound spectrum shows a broadband range of frequencies with highest levels in the very low (under 125 Hz) and low frequencies (200 to 1,000 Hz), and tonal levels around 6,000 Hz.

Table 14. Summary of 30-in. Gravina DTH Driving Measurements

Pile Id	Distance (m)	Lp,rms _{1s}	LE _{ss}	Lp,rms _{90%}	Lp,pk	Rate (Hz)	Duration (sec)	TL
S4-V1	10	174	162	178	192	14	~1,750	NR
	110	158	147	160	174			
	185	154	NR	NR	171			
	455	140	128	140	152			
	940	135	124	136	147			
S4-V2	10	173	161	177	191	14	~1,780	NR
	110	159	147	161	176			
	185	155	NR	NR	173			
	430	139	127	139	151			
	975	136	125	137	148			
Assigned Value	10	174	162	178	192	14	1,750	19.7
WFA Adjustment								
	LFC	HFC	VHFC	PW	OW			
All	-0.8	-15.2	-19.2	-6.4	-6.3			
Assigned at 10m	-0.6	-7.0	-12.9	-4.7	-7.6			

NR = not reported.

42-inch Diameter – Thimble Shoals SSV

DTH hammering through rock was conducted at Thimble Shoal along the Chesapeake Bay Bridge Tunnel in Virginia (Denes et al., 2019). Measurements were made for DTH driving of 5 piles, which two had an air bubble curtain in an attempt to reduce sound. The air bubble curtain was not

considered effective in reducing the DTH sounds. This study treated the sounds as only impulsive. Table 15 summarizes the DTH sound levels measured for this project.

- **Type of Piles Driven and Type of DTH Hammer Used:** The DTH driving of five 42-inch diameter piles were measured, where two of the piles were accompanied by an air bubble curtain. The make or model of the DTH hammer was not reported.
- **Locations from the Pile where the Measurements were Made:** The underwater sounds from DTH hammering were recorded using Autonomous Multichannel Acoustic Recorders (AMARs) deployed at approximately 10 m, 35 m, and 75 m from the piles.
- **Water Depths:** The water depth was not reported.
- **Duration of DTH Driving or Drilling:** The DTH hammering activity had a duration of approximately 720 seconds, with an estimated 5030 pulses, ranging from 4700 to 6800.
- **Strike Rate of the DTH Hammer Used:** The strike rate for the DTH hammering was approximately 7 Hz, based on the piles being struck about once every 143 m.
- **Background or Ambient Measurements Made:** Ambient sound levels were measured at a distance of 75 to 100 m from the piles, where the median continuous RMS background level was recorded as 123 dB with a general range of 118 to 130 dB. These levels include contributions from anthropogenic, natural, and biological sources.
- **Transmission Loss (TL):** Although the TL was reported, it is not considered reliable for far-field sound predictions (i.e., greater than 100 m) because the most distant measurement location was only about 75 m from the pile.
- **Frequency Spectrum:** Most of the sound energy was centered between 100 Hz to 1000 Hz, with additional sound energy around 1200 Hz. The spectra of DTH hammering with a bubble curtain appear flatter, which may indicate some attenuation of peak energy by the bubble curtain, although the overall measured levels did not show an effective reduction.

Table 15. Summary of 42-in. Thimble Shoals DTH Driving Measurements

Pile Id	Distance (m)	Lp,rms _{1s}	LE _{ss}	Lp,rms _{90%}	Lp,pk	Rate (Hz)	Duration (sec)	TL
C10P4	10*	NR	170.2	185.5	197.0	7	~4,700	NR
C9P5	10*	NR	162.6	179.5	188.0	7	NR	NR
C8P8	10*	NR	159.1	175.1	184.6	7	~1,400	NR
C8P6**	10*	NR	158.1	174.1	184.2	7	NR	NR
C8P7**	10*	NR	158.7	175.1	185.3	7	~2,100	NR
Reported	10	NR	164	180	190			NR***
Assigned	10	172****	164	180	190	7	2,700	--
WFA Adjustment								
	LFC	HFC	VHFC	PW	OW			
All	-1.9	-17.8	-27.1	-13.4	-19.3			

NR = not reported.

* Only levels computed from a regression at 10 m from pile reported.

** With air bubble curtain but not included in reported/assigned values.

*** Sound levels as function of range out to 75 m were reported but there was poor correlation with distance (r^2).

**** Computed based on pulse rate, assuming 7 pulses per second.

42-inch Diameter – Skagway WP&YR SSV

Construction of a new mooring dolphin system for the White Pass & Yukon Route (WP&YR) dock in Skagway, Alaska included installation of 42-inch diameter piles (Reyff and Heyvaert 2019). This was done by first using a vibratory driver, then an impact pile driving, and then DTH

driving. Rock tension anchors (smaller diameter) were installed below the piles. The new dolphin moorings extended the size of an existing cruise ship terminal. Table 16 summarizes the DTH sound levels measured for this project.

- **Type of Piles Driven and Type of DTH Hammer Used:** The DTH driving of two 42-inch diameter piles were measured. The make or model of the DTH hammer was not reported.
- **Locations from the Pile where the Measurements were Made:** Sound levels were measured for one pile at of about 65 to 120 m and then at various distances ranging from 12 m up to 1.4 kilometers from the second pile.
- **Water Depths:** The piles were driven in water depths of approximately 35 to 37 m at the pile. Sound propagated into the inlet that was several hundred meter deep away from the pile.
- **Duration of DTH Driving or Drilling:** The duration of DTH drilling varied, with recorded durations of 603 to 1077 seconds.
- **Strike Rate of the DTH Hammer Used:** The rate of the DTH hammering was typically around 10 to 11 Hz during the rock socket drilling sessions.
- **Background or Ambient Measurements Made:** Only spot measurements of ambient or background conditions were made. Ambient noise measurements made during calm conditions away from the pile were measured as an overall RMS level of 97 dB. During rough conditions when the DTH driving occurred, overall sound levels, caused mostly by strumming noise, were 126 dB dominated by low frequency sounds below 500 Hz, with highest levels below 50 Hz.
- **Transmission Loss (TL):** The computed TL from measurements from the DTH source were reported at 16.2 dB per decade ($B = 16.2$).
- **Frequency Spectrum:** The sound levels were mostly broadband with notable peaks around 80 Hz, 250 Hz, and 2,000 Hz. The DTH fundamental frequency, of 10 Hz, was at low end of the frequency scale.

Table 16. Summary of 42-in. Skagway WP&YR DTH Driving Measurements

Pile Id	Distance (m)	Lp,rms1s	LE _{ss}	Lp,rms90%	Lp,pk	Rate (Hz)	Duration (sec)	TL
MD4-V	76*	160	150**	NR	177	10	1,077	NR
MD4-V	76*	163	153**	NR	180			
MD4-V	122*	158	148**	NR	175			
MD4-V	122*	163	153**	NR	184			
MD5-V	32*	173	163**	NR	193	10	604	NR
MD5-V	47*	172	162**	NR	190			
MD5-V	104*	156	146**	NR	174			
MD5-V	1,400*	144	134**	NR	162			
MD5-V	1,400*	146	136**	NR	164	10		15.6
Reported	10*	179	169**	NR	203			
Assigned Value	10	174	164	178	194	10		15.6
WFA Adjustment								
	LFC	HFC	VHFC	PW	OW			
All 10-25m	-1.4	-14.3	-29.5	-9.8	-16.4			

NR = not reported.

* Measured from DTH driving point.

** Computed using 1-sec RMS using 10*Log(hammer rate).

42-inch Diameter – Portsmouth Naval Shipyard

The expansion and modification of a dry dock facility at the Portsmouth Naval Shipyard in Kittery, Maine included various marine construction activities that installed sheet piles, foundation piles, rock excavation (and borings), and mechanical rock removal (NAVFAC 2023). Drilling DTH methods using a mono-hammer were used to install 42-inch diameter casings. The casings served primarily as guides for rock removal rather than permanent installations. Sound levels for various positions are reported but many are extrapolated from other measurements using unreliable TL functions. Table 17 summarizes the DTH sound levels measured for this project.

- **Type of Piles Driven and Type of DTH Hammer Used:** Ten 42-inch diameter casings were installed using a DTH mono-hammer, specifically the Mincon MP340, for mechanical rock excavation. Only four measurements were useful in that they measured at distances close to the source. Distant measurements were affected by a localized air bubble curtain that was not near the DTH activity.
- **Locations from the Pile where the Measurements were Made:** Measurements were made from locations at 10 m from the pile and distant measurements up to 188 m, which were outside of the basin and the bubble curtain used during construction.
- **Water Depths:** The water depth for these activities ranged from 10 to 13 m.
- **Duration of DTH Driving or Drilling:** The duration of DTH activities varied from approximately 475 to 1711 seconds per event.
- **Strike Rate of the DTH Hammer Used:** The DTH mono-hammer operated with a strike rate of approximately 9.5 Hz, or once every 105 milliseconds.
- **Background or Ambient Measurements Made:** Ambient or background sound levels in the area were not reported.
- **Transmission Loss (TL):** TL was not computed for this activity.

- **Frequency Spectrum:** The spectral analysis indicated that the sound energy was fairly broadband, with peak energy levels observed in the range of 160 to 600 Hz and a narrower peak from 2000 to 4000 Hz.

Table 17. Summary of 42-in. Portsmouth Naval Shipyard DTH Driving Measurements

Pile Id	Distance (m)	Lp,rms _{1s}	LE _{ss}	Lp,rms _{90%}	Lp,pk	Rate (Hz)	Duration (sec)	TL
6	10	167*	158	167	184	9.5	475	NR
8	10	165*	155	166	182	9.5	1,711	NR
9	10	162*	152	162	178	9.5	837	NR
10	10	164*	154	164	178	9.5	1,127	NR
Reported	NR	NR	NR	NR	NR	NR	NR	NR
Assigned Value	10	164	155	165	181	9.5	1,200	
WFA Adjustment								
	LFC	HFC	VHFC	PW	OW			
Reported	NR	NR	NR	NR	NR			
Computed at 10m	-0.5	-8.8	-21.4	-5.8	-10.1			

NR = not reported.

* Computed based on pulse rate, assuming 9.5 pulses per second.

Rock Tension Anchor DTH Drilling

Rock tension anchor drilling occurs when the hole is advanced using DTH methods without a casing or pile. This is usually done when constructing rock tension anchors that extend below piles. There were five studies that involved rock tension anchor drilling. Each study is described below.

8-inch Diameter Rock Tension Anchor – Skagway WP&YR SSV

Drilling using DTH techniques for rock tension anchors to construct dolphin moorings as part of an existing cruise ship terminal as part of the WP&YR dock in Skagway, Alaska. The rock tension anchors were constructed below the 42-inch diameter mooring dolphins. Table 18 summarizes the DTH sound levels measured for this project.

- **Type of Piles Driven and DTH Hammer Used:** According to the initial project plans, 8-inch diameter holes were drilled for the rock tension anchors. However, photos indicate these might have been slightly larger at 10 inches in diameter. Measurements were made for the drilling of 3 tension anchors.
- **Water Depths:** The anchors were installed at a water depth of 35 m. Water depth away from the activity was over 100 m deep. The drilling occurred in bedrock about 17 to 23 m below the water.
- **Duration of DTH Driving or Drilling:** The duration of the DTH drilling for the rock tension anchors was approximately about 770 to 2200 seconds, with pulses occurring at a rate of 15 Hz. However, the hammer was not always active during the drilling. Sound levels reported only represent times that the hammer was active.
- **Locations from the Pile where the Measurements were Made:** Sound levels were measured from distances of 19 m and up to 110 m (and out to 600 m in one instance) from the mooring dolphin pile.

- **Strike Rate of the DTH Hammer Used:** The DTH hammer used for the rock tension anchors operated at a strike rate of 15 Hz. Note that sounds were not found to be impulsive more than 100 m from the pile.
- **Background or Ambient Measurements Made:** Ambient noise measurements made during calm conditions were measured as an overall RMS level of 97 dB. During rough conditions away from the activity, overall sound levels were 126 dB dominated by low frequency sounds below 500 Hz, with highest levels below 50 Hz. Sound generated by construction barges and equipment elevated the ambient levels near the measurement positions.
- **Transmission Loss (TL):** The TL was computed at 24.2 dB per decade ($B = 24.2$).
- **Frequency Spectrum:** The median $1/3^{\text{rd}}$ octave band levels at 10 m range across frequencies from 16 Hz up to 2,000 Hz. Notable peaks occurred around 16 Hz, 32, Hz, 80 Hz, and around 1000 Hz.

Table 18. Summary of 8-in. Skagway WP&YR DTH Drilling Measurements

Pile Id	Distance (m)	Lp,rms _{1s}	LE _{ss}	Lp,rms _{90%}	Lp,pk	Rate (Hz)	Duration (sec)	TL
MD4-NE	37*	138	NR	NR	153	15	~1,300	NR
	40*	135	NR	NR	147			
	88	128	NR	NR	143			
MD4-E	36	140	NR	NR	158	15	~770	NR
	89	123	NR	NR	NR			
	650	106	NR	NR	NR			
MD4-SE	36	148	NR	NR	160	15	~2,200	NR
	91	135	NR	NR	147			
	116	131	NR	NR	142			
Reported	10	156	144**	NR	170	15		24.2
Assigned Value	10	156	144	NR	170	15	2,200	24.2
WFA Adjustment								
	LFC	HFC	VHFC	PW	OW			
All at 36-40*	-3.8	-21.1	-23.6	-10.5	-10.8			
All at 10m	-1.3	-9.1	-19.4	-5.2	-11.0			

NR = not reported.

* Measured from DTH driving point.

** Computed using 1-sec RMS using $10 \cdot \log(\text{hammer rate})$.

8-inch Diameter Rock Tension Anchor – Tenakee Springs

Drilling using DTH techniques for rock tension anchors was performed to construct new bridge support float as part of improvements constructed for the Tenakee Springs Ferry Terminal in southeastern Alaska (Heyvaert and Reyff 2021). Measurements of rock tension anchor DTH drilling was conducted for the bridge support float piles. Note that measurements for the rock sockets installed within the 18-inch diameter piles were louder. Table 19 summarizes the DTH sound levels measured for this project.

- **Type of Piles Driven and Type of DTH Hammer Used:** There were four 8-inch rock tension anchors installed within both 24-inch diameter piles and two installed within 18-inch diameter piles. The anchors were installed using DTH drilling techniques.
- **Locations from the Pile where the Measurements were Made:** Measurements were conducted at about 10 m from the activity, about 100 to 200 m, and about 935 m. The

quieter sounds from tension rock anchor installation could not be clearly measured above background at the furthest distant positions.

- **Water Depths:** The installation occurred in water depths ranging from 5 to 6 m at the piles increasing up to 65 m deep at the furthest monitoring positions.
- **Duration of DTH Driving or Drilling:** Drilling durations varied, ranging from 400 to 900 seconds.
- **Strike Rate of the DTH Hammer Used:** The strike rate during rock anchor drilling was reported as approximately 22 Hz.
- **Background or Ambient Measurements Made:** Ambient noise measurements made during calm conditions were measured as an overall RMS level of 97 dB. Overall RMS sound levels were measured at 118 dB at the middle position and 104 dB at the distant position.
- **Transmission Loss (TL):** TL computations were 17.0 dB per decade distance increase (B=17) for the 18-inch diameter piles and 19.2 dB per decade (B=19.2) for the 24-inch piles, as measured out to 270 m.
- **Frequency Spectrum:** The 1/3rd octave band levels reveal most acoustic energy over the range of 63 to 1,000 Hz. Notable frequency peaks include 137 dB at 20 Hz, 40 Hz, 250 Hz and 1,000 Hz.

Table 19. Summary of 8-in. Tenakee Springs DTH Drilling Measurements

Pile Id	Distance (m)	Lp,rms1s	LE _{ss}	Lp,rms90%	Lp,pk	Rate (Hz)	Duration (sec)	TL
8-inch diameter Rock Tension Anchor								
R2 Battered	12	147	NR*	NR*	163	22	~880	NR
	270	121	NR*	NR*	135			
R1 Battered	10	149	NR*	NR*	164	22	~920	NR
	270	128	NR*	NR*	141			
Reported	10					22		17.0
24-inch diameter Rock Tension Anchor								
R-4	10	140	NR*	NR*	155	22	~400	NR
	260	114	NR*	NR*	128			
	930	NR	NR*	NR*	NR			
R-3	10	141	NR*	NR*	155	22	~500	NR
	255	114	NR*	NR*	129			
	925	NR	NR*	NR*	NR			
R-1	8	144	NR*	NR*	157	22	~900	NR
	265	114	NR*	NR*	128			
	935	NR	NR*	NR*	NR			
R-2	12	141	NR*	NR*	155	22	~900	NR
	265	114	NR*	NR*	129			
	935	NR	NR*	NR*	NR			
Assigned Value 18-in. dia.	10	149	--*	--*	164	22	900	17.0
Assigned Value 24-in. dia.	10	141	--*	--*	155	22	900	19.2
WFA Adjustment								
		LFC	HFC	VHFC	PW	OW		
18-in. dia.	10	-1.7	-13.1	-22.3	-9.5	-14.6		
24-in. dia.	10	-2.4	-18.2	-28.0	-12.6	-20.7		

NR = not reported because sounds were not distinguishable from ambient or background levels.

* Sounds were not found to be impulsive (i.e., impulsive levels were not greater than 3 dB above continuous levels).

10-inch Diameter Soil Tension Anchor – Auke Bay Ferry Terminal

Underwater measurements were made during the installation of soil anchors for 24- and 30-inch diameter piles that were previously vibrated and then impact driven for the Auke Bay Ferry Terminal near Juneau, AK (Greenbusch Group, Inc. 2021). DTH drilling was conducted to drill the soil tension anchors. The 30-inch diameter pile was driven in 3 segments for one day. Levels from all segments were averaged. Table 20 summarizes the DTH sound levels measured for this project.

- **Type of Piles Driven and Type of DTH Hammer Used:** There were two estimated 10-inch soil tension anchors installed using DTH drilling. Plans called for boreholes as being a minimum diameter of 6-inches, however, DOT&PF staff identified these as 10-inch holes. Measurements were made for one 24-inch pile and one 30-inch pile. The levels for the 24-inch diameter pile were much lower due to the battered nature of the pile, which sloped away from the measurements. For this reason, only the louder levels measured for the larger, vertical pile, were used in this report.
- **Locations from the Pile where the Measurements were Made:** Measurements were taken from distances of 10 m, a roving measurement from 153 to 660 m, and a far-field position

at 1,060 m from the drilling activities. However, DTH drilling sounds at 1,000 m were measured at similar levels as background sounds when DTH activities were not occurring. Therefore, the 1,000-m measurements may have been influenced by background sound.

- **Water Depths:** The water depth where these installations occurred was approximately 39 m. Sounds propagated over water that was more than 50 m deep.
- **Duration of DTH Driving or Drilling:** The duration of DTH activities for the 10-inch rock tension anchors ranged between about 3,200 seconds, with a typical event lasting around 3900 seconds.
- **Strike Rate of the DTH Hammer Used:** The DTH drilling was conducted at a strike rate of 17.5 Hz.
- **Background or Ambient Measurements Made:** Ambient sound levels in the area ranged from 92 to 145 dB, with an average level of 117 dB. Background levels were measured at the far field position, where DTH drilling sounds were measured to be 115 dB for both piles, even though the smaller pile had much lower near source levels. Therefore, ambient levels probably contributed to the DTH level measured for these piles.
- **Transmission Loss (TL):** The computed TL for the $L_{p,rms1s}$ was 17 to 18 dB per decade, while the TL for $L_{p,pk}$ was 22 dB per decade.
- **Frequency Spectrum:** The frequency spectrum showed sound levels across a range of frequencies from 400 Hz to 3,000 Hz, with notable peaks at 100 Hz and 800-2,000 Hz.

Table 20. Summary of 10-in. Auke Bay Ferry Terminal DTH Drilling Measurements

Pile Id	Distance (m)	$L_{p,rms1s}$	LE_{ss}	$L_{p,rms90\%}$	$L_{p,pk}$	Rate (Hz)	Duration (sec)	TL
N-1-B1 24-in. Battered	13	150*	138	152	166	17.5	Total ~2,500	12**
	87	139*	127	139	153			
	987	127*	115	129	139			
N3-V2 30-in. Vertical	10	162*	149	164	183	17.5	Total ~7,800	17**
	153 to 660	131*	119	133	148			
	1,060	128*	116	129	139			
Assigned Value	10	157	145	160	176	17.5	7,800	17***
WFA Adjustment								
	LFC	HFC	VHFC	PW	OW			
N3-V2 at 10m	-0.1	-6.1	-24.0	-2.5	-8.2			

* Computed using 1-sec RMS using $10 \cdot \log(\text{hammer rate})$.

** TL based on far-field measurement that was likely influenced by background sources.

*** Only louder, N3-V2 pile data used since it was vertical and louder at 10 m.

8-inch Diameter Rock Tension Anchor – Gravina Airport Ferry Layup

There was DTH drilling conducted for 3 rock tension anchors constructed for the north restraint dolphin for the Gravina Ferry Layup facility (Reyff and Ambaskar 2023). There was one vertical and two battered piles that made up this dolphin. Table 21 summarizes the DTH sound levels measured for this project.

- **Type of Piles Driven and Type of DTH Hammer Used:** There were three 8-inch rock tension anchors installed using DTH drilling.

- **Locations from the Pile where the Measurements were Made:** Measurements were taken from distances as close as 10 m up to 1000 m from the drilling activities. However, DTH drilling sounds could not be measured above elevated background sounds at 1,000 m.
- **Water Depths:** The water depth where these installations occurred was approximately 15 m. Sounds propagated over water that was more than 100 m deep.
- **Duration of DTH Driving or Drilling:** The duration of DTH activities for the 8-inch rock tension anchors ranged between about 3,500 to 4,500 seconds, with a typical event lasting around 3900 seconds.
- **Strike Rate of the DTH Hammer Used:** The DTH drilling was conducted at a rate of 22 Hz.
- **Background or Ambient Measurements Made:** Ambient sound levels in the area during daytime hours ranged from 110 to 116 dB. However, levels were above 120 dB at times when DTH activities occurred. There were active vessels and a dry dock facility nearby.
- **Transmission Loss (TL):** The computed TL for the $L_{p,rms1s}$ was 17.1 dB per decade, while the TL for $L_{p,pk}$ was 22.6 dB per decade.
- **Frequency Spectrum:** The frequency spectrum showed sound levels across a range of frequencies from 10 Hz to 2,000 Hz, with notable peaks at 25 Hz, 100 Hz and 400-1,000 Hz.

Table 21. Summary of 8-in. Gravina Ferry Layup DTH Drilling Measurements

Pile Id	Distance (m)	$L_{p,rms1s}$	LE_{ss}	$L_{p,rms90\%}$	$L_{p,pk}$	Rate (Hz)	Duration (sec)	TL
NRD-1	10	159	146	161	178	22	~4,500	NR
	80	136	NR	NR	149			
	350	130	NR	NR	143			
	1,000	NR	NR	NR	NR			
NRD-2	10	158	145	160	174	22	~3,500	NR
	80	136	NR	NR	161			
	350	131	NR	NR	NR			
	1,000	126	NR	NR	NR			
NRD-3	10	161	148	164	179	22	~3,670	NR
	80	136	NR	NR	157			
	350	132	NR	NR	NR			
	1,000	124	NR	NR	NR			
Reported	10	157	146	162	177	22	--	17.1
Assigned Value	10	157	146	162	177	22	3,900	17.1
WFA Adjustment								
		LFC	HFC	VHFC	PW	OW		
All	10 – 80	-0.8	-27.7	-34.9	-6.8	-7.4		
All	10	-0.3	-10.1	-30.0	-5.0	-12.9		

NR = not reported.

8-inch Diameter Rock Tension Anchor – Gravina Freight Facility

DTH drilling was also conducted for 4 rock tension anchors constructed for the outer dolphin pile at the Gravina Freight Facility (near the Gravina Airport Layup facility). There were two vertical and two battered piles that made up this dolphin. Table 22 summarizes the DTH sound levels measured for this project.

- **Type of Piles Driven and Type of DTH Hammer Used:** There were four total 8-inch rock tension anchors installed using DTH drilling. Two were for vertical piles and two were for battered piles.
- **Locations from the Pile where the Measurements were Made:** Measurements were made at distances as close as 10 m and out to 910 m from the drilling activities. Some DTH drilling sounds could not be measured above elevated background sounds beyond 110 m when currents were strong and/or boats were present.
- **Water Depths:** The water depth where these installations occurred was approximately 20-23 m. Sounds propagated over water along the channel that was no more than 30 m deep.
- **Duration of DTH Driving or Drilling:** The duration of DTH activities for the 8-inch rock tension anchors ranged between about 3,200 to 4,300 seconds, with a typical event lasting around 3,600 seconds.
- **Strike Rate of the DTH Hammer Used:** The DTH drilling was conducted at a steady strike rate of 22 Hz.
- **Background or Ambient Measurements Made:** Ambient sound levels in the area during daytime hours ranged from 110 to 116 dB. However, levels were above 120 dB at times when DTH activities occurred. There were active vessels and a dry dock facility nearby.
- **Transmission Loss (TL):** The computed TL for the $L_{p,rms_{1s}}$ was 19.1 dB per decade, while the TL for $L_{p,pk}$ was 18.5 dB per decade.
- **Frequency Spectrum:** The frequency spectrum showed sound levels across a range of frequencies from 20 Hz to 2,000 Hz, with notable peaks at 20 Hz, 50 Hz and 125-2,000 Hz.

Table 22. Summary of 8-in. Gravina Freight Facility DTH Drilling Measurements

Pile Id	Distance (m)	Lp,rms _{1s}	LE _{ss}	Lp,rms _{90%}	Lp,pk	Rate (Hz)	Duration (sec)	TL
S4 Vert 1E	10	154	142	155	169	22	~4,300	NR
	30	146	134	147	158			
	110	136	NR	NR	NR			
	390	NR	NR	NR	NR			
	870	NR	NR	NR	NR			
S4 Vert 2W	10	159	147	160	173	22	~3,600	NR
	30	148	136	149	158			
	110	136	NR	NR	147			
	390	NR	NR	NR	NR			
	870	NR	NR	NR	NR			
S4 Batt E	10	153	141	154	166	22	~3,200	NR
	30	146	136	149	159			
	110	134	NR	NR	NR			
	360	123	NR	NR	138			
	910	120	NR	NR	132			
S4 Batt W	10	153	141	155	168	22	~3,900	NR
	30	146	133	146	157			
	110	132	NR	NR	147			
	360	123	NR	NR	137			
	910	118	NR	NR	134			
Reported	10	155	143	156	169	--	--	19.1
Assigned Value	10	155	143	156	169	22	3,600	19.1
WFA Adjustment								
		LFC	HFC	VHFC	PW	OW		
All	10-110	-1.9	-27.9	-33.4	-9.5	-9.8		
All	10	-0.4	-11.7	-33.7	-5.9	-14.8		

NR = not reported.

33-inch Diameter – DTH Drilling at Ward Cove near Ketchikan, Alaska

Two 33-inch diameter piles were installed to construct a new ship terminal at Ward Cove, which is near Ketchikan, in southeastern Alaska (Guan et al., 2022). DTH drilling was used to construct shafts below the piles. Table 23 summarizes the DTH sound levels measured for this project.

- **Type of Piles Driven and Type of DTH Hammer Used:** Two 33-inch diameter shafts were drilled below approximately 48-inch diameter steel piles. A DTH hammer with a 33-inch diameter bit was used to advance a drilled hole through bedrock below the pile after initial advancement by conventional vibratory and impact hammers through approximately 15-m deep sand, silt, and loose sediments.
- **Locations from the Pile where the Measurements were Made:** Sound measurements were made at distances of 10 m, 200 m, and partially at 1,300 m from the pile. However, data from 1,300 m were not usable due to contamination from nearby vessel sounds.
- **Water Depths:** The water depth for these installations was about 30 m.
- **Duration of DTH Driving or Drilling:** The DTH drilling for these shafts took approximately 147 minutes (8820 seconds) for active drilling.
- **Strike Rate of the DTH Hammer Used:** The strike rate for the DTH hammer during these operations was about 10 to 12 Hz, which is approximately once every 83 to 100 milliseconds.

- **Background or Ambient Measurements Made:** The ambient sound levels in the area were noted, with general levels around 120 dB, except in regions with strong tidal currents where the ambient noise level could vary significantly. There was noise from nearby vessels.
- **Transmission Loss (TL):** The transmission loss coefficients were reported for $L_{p,rms_{1s}}$ and $L_{p,pk}$, ranging from 13.1 to 15.4 dB, but these were based on partial measurements at 1,300 m. The measurements at 1,300 m only included the loudest portion of the DTH drilling because other periods were not used due to background noise. These were combined with the complete set of measurements at 10 m and 200 m.
- **Frequency Spectrum:** The frequency spectrum predominantly showed most acoustic energy concentrated below 1 kHz, with highest levels at the lowest frequencies.

Table 23. Summary of 33-in. Ward Cove DTH Driving Measurements

Pile Id	Distance (m)	$L_{p,rms_{1s}}$	LE_{ss}	$L_{p,rms_{90\%}}$	$L_{p,pk}$	Rate (Hz)	Duration (sec)	TL
137E	10	147	138	150	158	10-12	8,820	13.1**
	200	132	122	134	143			
	1,300*	119*	109*	122*	130*			
131W	10	151	142	155	163	10-12	9,360	15.4***
	90	136	127	140	149			
	150	133	124	137	147			
Reported	10	147-151	138-142	150-155	158-163			
Assigned	10	149	140	153	161	12	8,800	--****
WFA Adjustment								
Pile ID	LFC	HFC	VHFC	PW	OW			
--	NR	NR	NR	NR	NR			
Computed at 10m	-6.5	-28.3	-39.5	-31.0	-22.0			

NR = not reported.

* Partial measurement that only included loudest DTH sounds not affected by background noise.

** Computed using partial measurement at far-field position.

*** Computed for measurements close to the pile.

**** Not enough measurements in far field to compute TL.

Sound Attenuation

Sound attenuation using air bubble curtains was used on two projects that involved DTH driving.

The DTH driving of 42-inch diameter piles at Thimble Shoals involved five piles, where two were installed using bubble curtains. There was considerable variation in sound level by location. The loudest locations did not use a bubble. DTH hammering at one location without a bubble curtain was approximately the same level as two measurements with a bubble curtain, so an effect of the bubble curtain could not be determined from the measured levels. Examination spectral band levels of the signals found that the primary sound energy is between 100 and 1000 Hz, appeared to be flattened, suggesting the bubble curtain could be attenuating sound levels. This effect is considered subtle and a reduction in overall sound levels could not be quantified.

DTH driving for the expansion of Dry Dock 1 at the Portsmouth Naval Shipyard in Kittery, Maine included an air bubble curtain system to reduce underwater sound levels. However, this air bubble curtain was established between the 10-m position and the far-field hydrophone. The far-field hydrophone position varied, and therefore, the effectiveness of the bubble curtain in attenuating

sound could not be quantified. There was no condition in the far-field representing unattenuated conditions.

Based on studies conducted to date, there are no reliable measurements of air bubble curtains reducing sound levels from DTH activities.

Upset Conditions

DTH driving under upset conditions was documented during DTH driving of a 24-inch diameter casing for the Gravina Freight Facility project. Two casings were installed. DTH driving for the first casing was much louder because the pilot bit was making direct contact with the casing, rather than direct contact directly with bedrock below. The direct transmission of sound into the casing was 5 to 7 dB louder. Since the pile took much longer to drive, the LE_{cum} was 15 to 16 dB louder. This DTH event was not considered representative of DTH driving that would typically occur.

OVERALL DTH SOUND LEVELS

DTH driving and drilling sounds are summarized in Table 24, along with the hammer strike frequency, duration, and transmission loss coefficient. This summary is based on averaging median sound levels for representative events. The range of overall measured sound levels is also reported. Unusual events or quiet events were not included in this averaging. Some DTH measurements included several events, so the reported average sound levels were weighted based on the number of representative events.

Table 24. Summary of DTH Measurements from All Available Measurements (Reported Median Levels)

Pile/Casing Diameter	Number of Measurements	Lp,rms _{1s}			LE _{ss}			Lp,rms _{90%}			Lp,pk			Rate (Hz)	Approx. Duration (sec)	TL
		Avg	High	Low	Avg	High	Low	Avg	High	Low	Avg	High	Low			
DTH Driving																
18	2	158	156	158	146	145	147	162	161	162	172	170	173	13	5,400	--
24	15	167	156	171	156	149	160	173	163	174	184	176	186	13	2,800	18.6
30	2	174	173	174	162	161	162	178	177	178	192	191	192	14	1,800	19.7
42	8	173	161	178	164	152	170	180	162	186	191	178	197	8	5,400	15.6
DTH Drilling																
8-10	18	155	139	161	145	141	148	161	154	164	172	155	179	20	2,700	18.9
33	2	149	147	151	140	138	142	153	150	155	161	158	163	12	8,800	14.3

Note that *High* and *Low* represent the range in reported median levels for each DTH event.

The relationship between pile or casing diameter and sound level is not clear. This relationship was examined using the RMS continuous level (e.g., $L_{p,rms1s}$) reported for each measurement. Based on the average of median sound levels for each pile size, the 30-inch diameter DTH driving sounds were the loudest. Note that unusual events were not included in these averages. Figure 10 displays the relationship between the continuous DTH driving sound level and pile diameter (in inches). A statistical regression using all measured values, that weights these based on the number of measurements, shows decent agreement between sound level and pile diameter. Note that there are not an equal number of measurements for each pile size. The relationship between DTH driving level for LE_{ss} , $L_{p,rms90\%}$ and $L_{p,pk}$ were found in Table 25. Based on the data collected, use of this relationship would tend to overpredict levels for smallest piles and underpredict levels for piles around 30 inches in diameter.

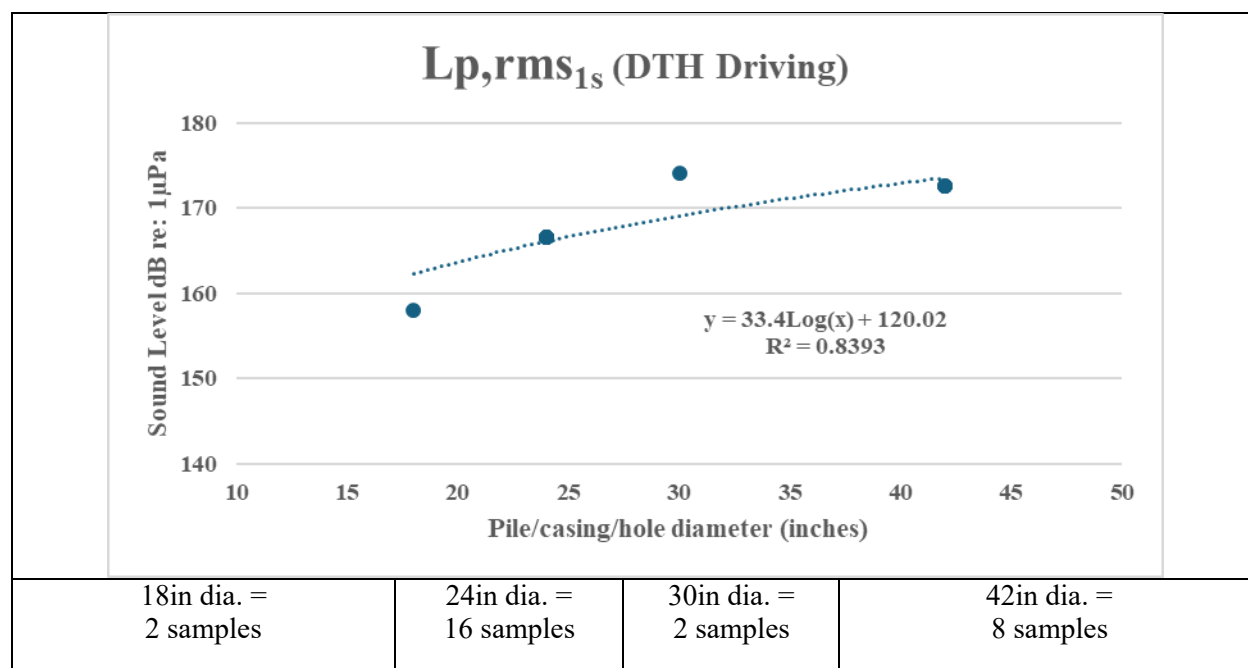


Figure 10. Relationship between DTH pile driving sound level ($L_{p,rms1s}$) and pile diameter

Table 25. Relationship Between DTH Driving Sound Level and Pile/Casing Diameter

Sound Level Descriptor	Relationship (x = pile diameter in inches)	r ² value
$L_{p,rms1s}$	$33.4 \text{ Log}(x) + 120\text{dB}$	0.8393
LE_{ss}	$39.9 \text{ Log}(x) + 100\text{dB}$	0.9083
$L_{p,rms90\%}$	$35.7 \text{ Log}(x) + 122\text{dB}$	0.8729
$L_{p,pk}$	$38.5 \text{ Log}(x) + 130\text{dB}$	0.7911

For DTH drilling, there is no relationship between hole diameter and sound levels. Mostly because drilling of holes associated with larger 33-inch diameter piles had similar or lower sound levels than those associated with 8- and 10-inch diameter holes. There were a fairly large number of measurements made for DTH drilling of 8- to 10-inch diameter holes (for rock tension anchors) that yielded a large range of measurements results. The median values reported for ranged from 141 to 162 dB, with a weighted mean value of 156 dB. There were only two measurements made

for drilling of 33-inch diameter holes and these had an average median value that was lower than those for smaller rock tension anchor holes.

DTH IMPULSIVITY

NMFS groups DTH sounds into impulsive and non-impulsive (or continuous) sounds. Impulsive sounds have much lower sound thresholds than non-impulsive sounds for AUD INJ impacts to marine mammals, as currently regulated by NMFS. There currently are no non-impulsive sound thresholds that apply to fish. Impact pile driving sounds are clearly impulsive, producing transient, brief (less than one second), broadband sounds that consist of high peak sound pressure with rapid rise time and rapid decay. DTH sounds are similar but occur more frequently and usually with lower amplitude.

The studies evaluated in this report show evidence that as DTH sounds propagate away from the pile, they become less impulsive. This occurs as the higher frequency components decay at a faster rate, non-linear acoustical spreading occurs, all while background sounds contribute to the quieter far-field environment.

Most of the studies reviewed analyzed DTH sounds as impulsive. However, not all of the studies demonstrated the impulsivity of sounds in the very far-field. Examination of pressure waveforms from measurements of DTH driving of 42-inch diameter piles in deep water at Skagway (Reyff and Heyvaert 2019) clearly showed impulsive sounds at 1,600 m from the pile. This activity produced some of the loudest DTH sounds measured and occurred in the deepest water where water depth at 1,600 m exceeded several hundred meters. Measurements for DTH driving of 24-inch diameter piles at Tenakee Springs indicated impulsive sounds at the furthest measurement positions of almost 1,000 m. This was consistent with measurements at Metlakatla (Miner 2023) for 24-inch diameter piles measured out to 1,000 m and Biorka Island for 24-inch diameter piles measured out to 200 m (Guan and Miner, 2020). However, measurements for 24- and 30-inch diameter piles at Gravina (Reyff and Ambaskar 2023) found sounds were not impulsive beyond about 500 m.

Measurements for DTH drilling sounds (typically rock tension anchor construction) show less impulsivity, as reported for measurements at Skagway (Reyff and Heyvaert 2019), Tenakee Springs (Heyvaert and Reyff 2020), and at Gravina (Reyff and Ambaskar 2023). The primary reasons are that levels are about 15 to 20 dB lower and the frequency of pulses is much greater at around 20 Hz. Measurements close to the pile (i.e., within about 100 m) were found to be impulsive. Three studies clearly measured DTH drilling signals in the very far field. Skagway tension anchors that were 10 inches in diameter were not found to be impulsive beyond 91 m; however, there was elevated background sound. Tenakee Springs measured two different sets of DTH drilling for tension anchors and identified the sounds as continuous since the measured difference between impulse and 1-second RMS levels were only 2 to 3 dB. The authors noted that the sounds had impulsive characteristics. Measurements at two locations for Gravina found that DTH drilling sounds for 8-inch rock tension anchors were not impulsive beyond about 80 m from the pile. Measurements of 10-inch diameter soil anchors at Auke Bay reported sound levels out to about 1,000 m. However, there was no examination of the sounds to determine if they were

impulsive. Background sound levels for Auke Bay were within 10 dB of the measured DTH drilling sound levels, indicating a possibility that they were not impulsive. Measurements at Ward Cove (Guan et al., 2022) for 33-inch diameter DTH drilling found both impulsive and non-impulsive sounds. The examination of the signals showed low amplitude sounds with high frequency of strike rates.

While DTH driving appears to be impulsive in most cases out to far distances, DTH drilling sounds are found to be less impulsive. There are two reasons for this: First, the DTH drilling sounds are considerably lower in amplitude, by about 15 to 20 dB. Second, the percussive hammer rate is much higher at about 20 Hz (vs about 10 Hz), so sound pulses can blend with each other to some extent. The amplitude of background sounds can affect the impulsive nature in the very far field, especially when overall sound level is within 10 dB of the DTH sounds.

DTH SOUND PROPAGATION

The rate at which sound diminishes in level away from the pile in this report is described as the transmission loss, or TL, which is defined by coefficient for a Log_{10} rate of sound decay as distance increases from the source. For pile driving, NMFS recommends a TL coefficient of 15 when site-specific information is not available. Under current practice, NMFS recommends this approach for DTH sounds, both DTH driving and drilling (NMFS 2022).

The source of sound from DTH driving or drilling is different than that of pile driving. Pile driving sound is generated by a hammer striking a pile and transmitting energy through the pile and into the water and the substrate below. DTH driving sounds are generated by a percussive hammer striking hard ground or bedrock below the water and transmitting sound into the pile and into water as well as into the substrate and then into the water. With DTH drilling, there is less contact between the percussive hammer and a casing or pile. The sound environment generated near the pile is quite complex and may not be adequately described using measurements that are so close to the source.

Most of the monitoring reports reviewed included distant measurements so that TL coefficients could be computed. There are several reports that included measurements away from the pile but were not considered adequate for computing TL coefficients. For example, Thimble Shoals included measurements at about 10 to 75 m, which were not considered adequate for describing sound attenuation over several hundred meters. Similarly, measurements for Biorka were made out to 200 m.⁶

The average TL coefficient computed for each study is shown in Table 26. The critical sound descriptors in terms of impacts are the SELs that leads to Level A impacts and fish injury and the continuous RMS level that leads to Level B impacts. The average TL coefficient for DTH driving ranged from 15.5 to 19.9, when considering both $L_{p,rms,1s}$ and LE_{ss} . DTH drilling had generally higher TL coefficients, ranging from 17 to 24, apart from one measurement that was 14.3 (Ward Cove).

⁶ Note that measurements were attempted at about 1,200 m but DTH sounds could not be detected above background.

Table 26. TL Coefficients Calculated for Different Studies

Study	Pile Diameter (inches)	No. of Samples	Lp,rms _{1s}	LE _{ss}	Lp,rms _{90%}	Lp,pk
DTH Driving						
Biorka	18	2	NM	NM	NM	NM
Gravina	24	1	19.5	19.9	20.4	21.5
Gravina (upset)	24	1	19.3	19.8	20.9	22.0
Kodiak	24	7	18.9	NM	NM	NM
Metlakatla	24	3	15.5	15.5	15.7	15.9
Tenakee	24	4	19.1	19.4	20.3	19.8
Gravina	30	2	19.7	19.7	21.7	23
Skagway	42	1	16.2	16.2	16.2	16.7
Thimble Shoals	42	3	NM	NM*	NM	NM
Navy Portsmouth	42	4	NM	NM	NM	NM
DTH Drilling						
Skagway WP&YR (42in Pile)	10	2	24.2	NM	NI	NI
Tenakee (18in Pile)	8	2	17.0	NI	NI	18.3
Tenakee (24in Pile)	8	4	19.2	NI	NI	NI
Auke Bay (30in Pile)	10	3	17	17	18	22
Gravina (30in Pile)	8	3	17.1	NI	NI	22.6
Gravina (30in Pile)	8	4	19.1	NI	NI	18.5
Ward Cove	33	2	14.3**	14.5**	14.2**	13.6**

NM = not measured. NI = non-impulsive sound; therefore, impulsive metric not measured.

* TL coefficient only reported for distances of less than 100 m.

** Ward Cove measurements at 1,300 m were only for the beginning portion that was louder.

The TL coefficients for each measurement were averaged or weighted based on the number of measurements for that average TL coefficient. This yielded the TL coefficients for DTH driving and drilling reported in Table 27.

Table 27. Weighted Average TL for DTH Sounds (all pile sizes)

DTH Activity	L _{p,rms1s}	LE _{ss}	L _{p,rms90%}	L _{p,pk}
Driving	17.5	16.9	17.7	18.0
Drilling	18.3	--*	--*	--*

* Not enough data. Note DTH drilling sounds appear to have relatively low levels with respect to Level A impacts and Level B impacts are assessed using continuous sounds, L_{p,rms1s}.

The size of areas where impacts to marine mammals occur is mostly dependent on the amplitude of the source sound level and the attenuation rate of sound.

Note that the TL coefficients reported in Tables 26 and 27 are based on the measurements made out several hundred to over 1,000 m. Some studies (Heyvaert and Reyff 2021) and (Reyff and Ambaskar 2023) show that even though TL coefficients were greater than 15, sounds at intermediate positions of about 100 to 200 m indicated a lower TL coefficient. The example shown in Figure 11 shows the sound level drop off with distance for 24-inch diameter casing DTH driving and Figure 12 shows the drop off for 8-inch diameter rock tension anchor DTH drilling (Reyff and Ambaskar 2023). This example illustrates that DTH driving may have a higher TL coefficient for intermediate positions of around 100 to 300 m. This does not appear to be the case for DTH drilling activity.

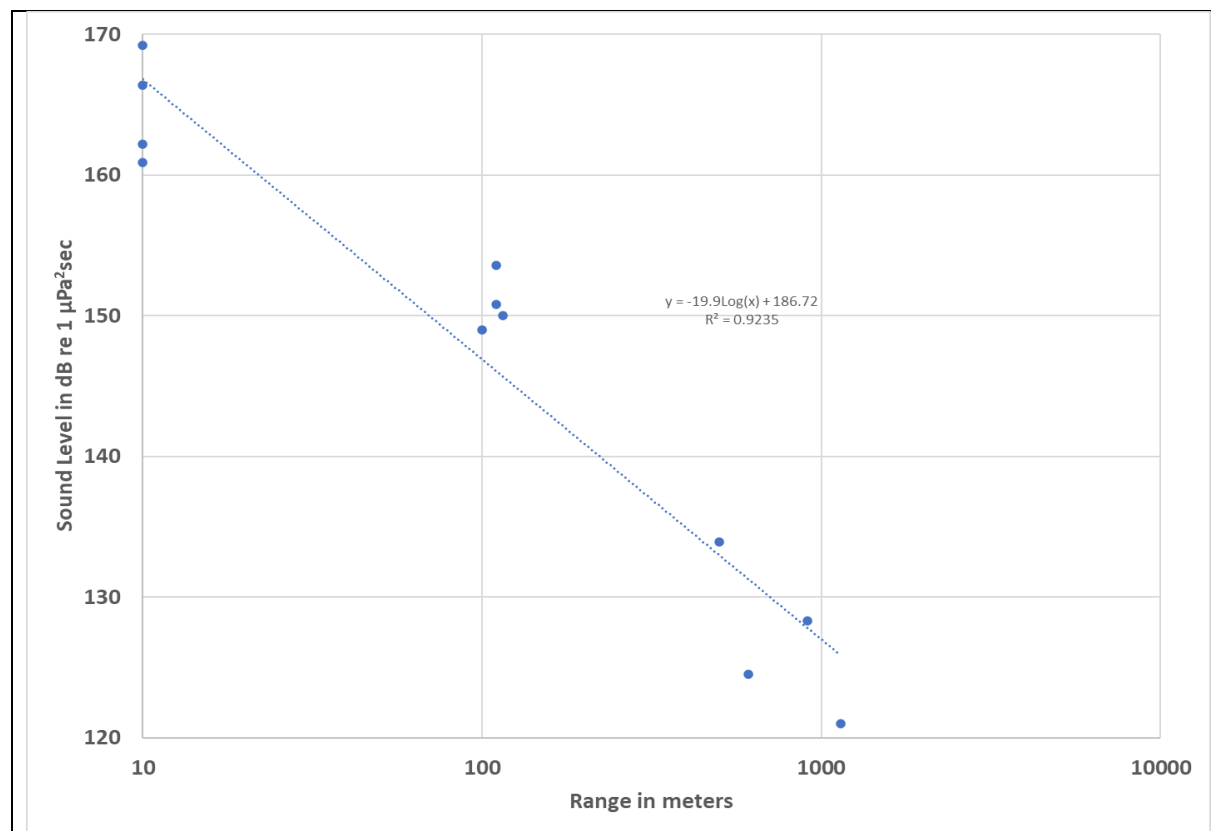


Figure 11. Example of sound transmission over distance for DTH driving of a 24-inch diameter pile at Gravina Freight Facility

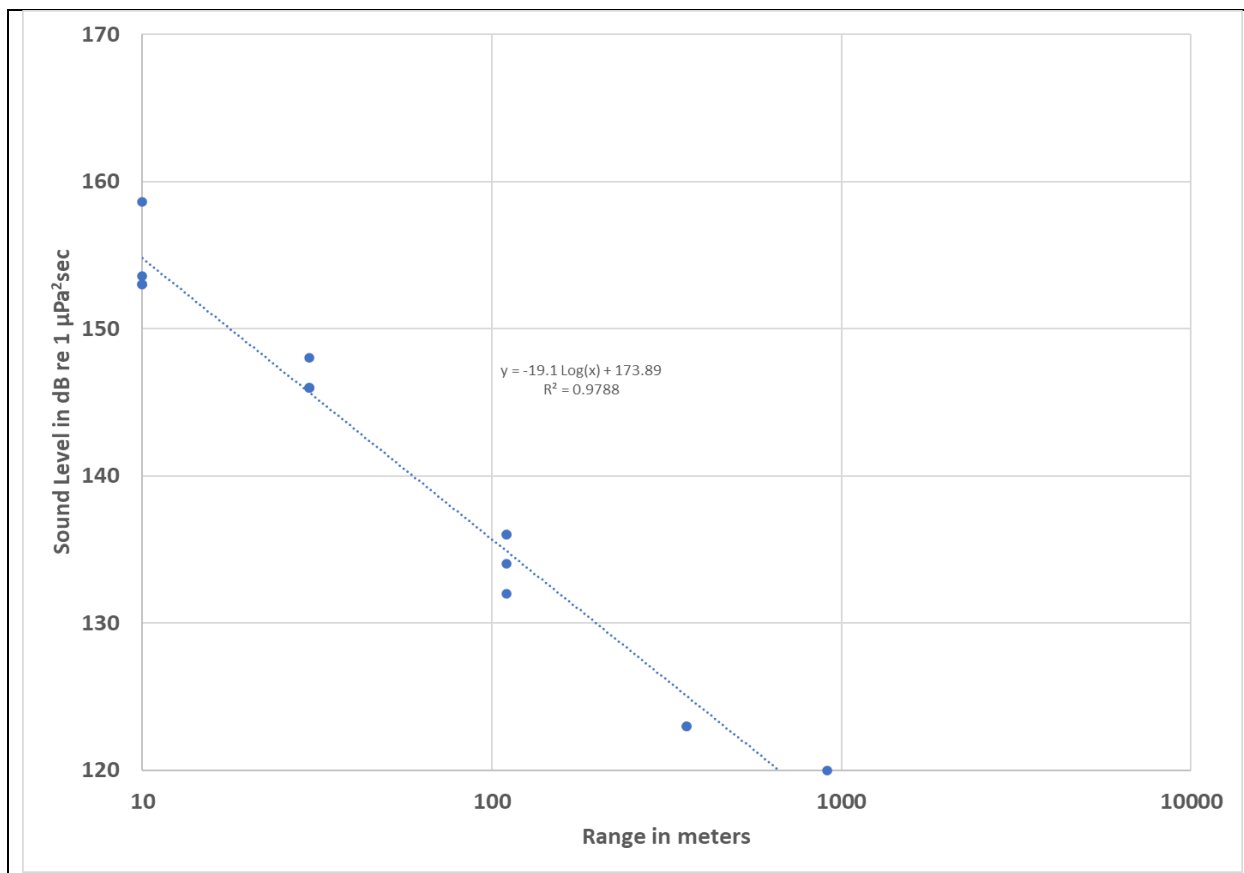


Figure 12. Example of sound transmission over distance for DTH drilling for an 8-inch diameter rock tension anchors at Gravina Freight Facility

DTH ACOUSTIC FREQUENCY CONTENT

Most studies reviewed provided spectral data as either sound pressure levels in narrow bands or 1/3rd octave band centers. In evaluating these reports, 1/3rd octave band plots and narrow band plots were developed. Most measurements revealed a fairly broadband signal for frequencies below about 2,000 Hz. Some measurements were dominated by the very low frequency sounds, typically at the hammering frequency, with harmonics spanning the lower frequency range. Note that some reports analyzed the sounds from single pulses, so they do not reveal the very low frequency nature of these repetitive sounds. Some measurements exhibited broadband sound energy well above 1,000 Hz, although, all measurements revealed most acoustic energy was under 1,000 Hz.

The acoustic frequency content is important for assessing Level A impacts to marine mammals. As previously described, NMFS uses marine mammal auditory weighting functions to assess the potential for onset of TTS and AU D INJ.

Table 28 presents the WFAs associated with DTH driving. There is a considerable range in the data, with the Navy Portsmouth data considered an outlier, as the WFAs were more extreme for all hearing groups. The average WFA along with a range of statistical exceedances were computed.

These are compared to the NMFS default WFAs recommended by NMFS in their User Spreadsheet (Version 3.1) for assessing the onset of AUD INJ from anthropogenic sounds. The WFAs associated with DTH driving shown in Table 28 show the need for substantial adjustments for pinniped hearing groups.

Table 28. Computed WFAs for DTH Driving Projects

Report	Diameter	Unweighted Level	Frequency WFAs (at 10 m) in dB re: 1 μ Pa ² sec				
			Cetaceans			Pinnipeds	
		LE _{ss}	LF	HF	VHF	Phocid	Otariid
Biorka	18	146	-2.8	-21.8	-31.5	-15.4	-24.3
Kodiak	24	154	-0.3	-10.6	-23.3	-5.5	-13.0
Tenakee	24	159	-2.9	-9.4	-16.9	-7.7	-10.0
Metlakatla	24	155	-1.4	-14.1	-27.5	-9.0	-16.4
Gravina	24	164	-1.3	-14.0	-26.6	-8.6	-16.4
Gravina	30	162	-0.6	-7.0	-12.9	-4.7	-7.6
Skagway	42	164	-1.4	-14.3	-29.5	-9.8	-16.4
Thimble Shoal	42	163	-1.9	-17.8	-27.1	-13.4	-19.3
Navy Portsmouth	42	155	-0.5	-8.8	-21.4	-5.8	-10.1
		Average	-1.5	-13.1	-24.1	-8.9	-14.8
		50th Percentile	-1.4	-14.0	-26.6	-8.6	-16.4
		75th Percentile	-0.6	-9.4	-21.4	-5.8	-10.1
		90th Percentile	-0.5	-8.5	-16.1	-5.3	-9.6
		NMFS (2.0 kHz single frequency WFA)	-0.03	-3.45	-21.19	-0.80	-5.23

WFAs computed from DTH drilling sounds are shown in Table 29. As with DTH driving, there is a considerable range in WFAs for DTH drilling. The Ward Cove data for DTH drilling were considered an outlier and not considered for averaging or statistical analysis. DTH drilling WFAs indicate that adjustments could be made for high-frequency cetaceans and for pinnipeds. Note that DTH drilling sounds are, for the most part, continuous sounds that have much higher thresholds. Therefore, the application of WFAs to these sounds are not likely to affect the prediction of Level A areas.

Table 29. Computed WFAs for DTH Drilling Projects

Report	Diameter (inches)	Unweighted Level	Frequency WFAs (at 10 m) in dB re: 1μPa ² sec				
			Cetaceans			Pinnipeds	
		LE _{ss}	LF	HF	VHF	Phocid	Otariid
Skagway	10	144	-1.3	-9.1	-19.4	-5.2	-11.0
Tenakee 18in	8	NM	-1.7	-13.1	-22.3	-9.5	-14.6
Tenakee 24in	8	NM	-2.4	-18.2	-28.0	-12.6	-20.7
Auke Bay	10	151	-0.1	-6.1	-24.0	-2.5	-8.2
Gravina	8	146	-0.3	-10.1	-30.0	-5.0	-12.9
Gravina	8	143	-0.4	-11.7	-33.7	-5.9	-14.8
Ward Cove*	33	140	-6.5	-28.3	-39.5	-22.0	-31.0
		Average	-1.1	-11.4	-26.2	-6.8	-13.7
		50th Percentile	-0.9	-10.9	-26.0	-5.6	-13.8
		90th Percentile	-0.2	-7.6	-20.8	-3.7	-9.6
		NMFS (2.0 kHz)	-0.03	-3.45	-21.19	-0.80	-5.23

* WFAs for Ward Cove were considered an outlier and not included in WFA calculations.

Use of single-frequency WFAs currently recommended by NMFS will generally overestimate the extent of Level A impacts. This overestimate appears to be about less than 1 dB for low-frequency cetaceans, 3 to 15 dB for high-frequency cetaceans, -2 to +12 dB for very high-frequency cetaceans, and +6 to +7 dB for pinnipeds. In general, the default WFAs would over estimate impacts to high-frequency cetaceans and pinnipeds. NMFS (2020) acknowledges that the use of the default WFAs in the User Spreadsheet are likely conservative.

USE OF DTH INFORMATION FOR ACOUSTIC ASSESSMENTS

This research report reviewed all available acoustical data associated with DTH driving and drilling activity in water. As recommended by Guan et al., 2022, sound types were divided into DTH driving activities that are impulsive and DTH drilling activities that are mostly non-impulsive but have impulsive characteristics. There were 11 reports reviewed that provided acoustical data for DTH systems. Together, these represented measurements for 28 DTH driving events and 20 DTH drilling events. Variables identified that influence the acoustical impacts from DTH activities are discussed in this section.

DTH Activity

For marine mammals, continuous sounds are associated with lower thresholds that address potential injury and behavior. There are no thresholds that currently apply to fish for continuous sounds. Therefore, continuous sounds, such as those associated with DTH drilling away from the source will have less impact due to the nature of the sound. Furthermore, DTH drilling was found to have lower source sound levels. While DTH drilling is considered impulsive near the source, the impacts, in terms of onset of AUD INJ, likely do not extend much beyond 100 m. The average of median continuous RMS levels for DTH drilling sounds were found to be 2 to 18 dB lower than those for DTH driving.

Source Level

The average of median sound levels at 10 m were computed for each pile size for DTH driving and drilling. A relationship between pile diameter and sound levels was established only for DTH driving. There simply was not enough data to evaluate that relationship for DTH drilling, although measurements at Ward Cove and Tenakee Springs indicate that there really is not a relationship between hole diameter and sound level for DTH drilling.

Transmission Loss Rate

The rate of sound propagation from DTH activity was found to be mostly greater than the practical spreading loss TL coefficient of 15 recommended by NMFS when considering the entire range that would extend beyond 1,000 m. There are some indications that sounds for DTH driving fall off at a lower rate closer to the pile or casing. Some measurement data sets did not include adequate data to compute the TL rate between sound level and distance. The computed TL coefficients were found to be greater for DTH drilling sounds than DTH driving.

Weighted Frequency Adjustments

The weighted frequency adjustments are always negative, in that they reduce the sound level compared to the threshold. NMFS currently uses adjustments that range from almost 0 dB to -21 dB, depending on the hearing type. In most cases, the WFAs for DTH activities were found to be greater than those recommended by NMFS. The most significant differences, of -5 dB, were for high-frequency cetaceans and pinnipeds.

Hammer Frequency and Duration

There are two ways to compute LE_{cum} to evaluate onset of AUD INJ impacts: (1) use of LE_{ss} and the number of hammer pulses and (2) Use of the SEL per second (or Lp_{rms1s}) and the number of seconds that the impulsive DTH activity occurs. For (1) above, hammer frequency and duration are key values. Use of (2) requires only duration (in seconds) values.

Generally, smaller piles/holes required a greater hammering frequency. The smaller diameter rock tension anchor holes were associated with hammering frequencies of about 20 Hz. DTH driving for 18- to 30-inch diameter holes were associated with hammering frequencies of about 13 to 14 Hz. The largest, 42-inch diameter holes were associated with hammering frequencies of about 9 Hz.

In terms of duration, there was no relationship between DTH driving or drilling duration and pile diameter. This is likely more specific to the depth of the hole requiring DTH driving or drilling, hardness of the substrate, and the effectiveness of the DTH drilling equipment. DTH driving times ranged from about 540 to 6,300 seconds. DTRH drilling times ranged from 900 to 4,000 seconds.

EXTENT OF SOUND IMPACTS FROM DTH ACTIVITIES

The extent of sound impacts from DTH activities depends on the type of activity, size of the pile or casing, the sound TL rate, the frequency content of the sound (i.e., WFA), and the species that receives the sound. A sensitivity test for DTH scenarios was conducted to provide an estimation

of underwater sound impacts: (1) DTH driving of a 24-inch diameter pile and (2) DTH drilling for an 8-inch diameter rock tension anchor.

The extent of sound impacts to marine mammals and fish were computed based on the SEL_{ss} at 10 m, the TL, the WFAs for each hearing group, the hammer strike frequency, and a duration of 4 hours per day. Note that there are no injurious impacts to fish for DTH drilling because the SEL_{ss} is below 150 dB, which is considered effective quiet. Note that L_{p,pk} associated with DTH driving and drilling are typically below 200 dB. The loudest levels measured at 10 m were 197 dB. Therefore, L_{p,pk} would not exceed thresholds beyond 10 m from the activity. Behavioral impacts to marine mammals were based on application of continuous RMS sound levels (e.g., L_{p,rms1s}) and the TL coefficients.

24-inch Diameter DTH Driving

Table 30 shows the extent of sound levels for the DTH driving of a 24-inch diameter casing or pile using a strike rate of 13 Hz. Two sets of predictions were made. One set uses NMFS 2022 DTH guidance along with the 2024 User Spreadsheet (Version 3.1), that has a source level of 159 dB at 10 m and uses the default WFAs based on a frequency cutoff of 2 kHz. The other prediction is based on data summarized in this report that uses the 2024 User Spreadsheet with a source level of 156 dB LE_{ss} at 10 m, a TL coefficient of 18.6, and WFAs for each hearing group. Table 30 shows substantial differences. For the calculation of impact zones, the TL coefficients computed in this report are based on all measurements made from about 10 m to 1,400 m. However, some studies involving DTH driving sounds (Heyvaert and Reyff 2021) and (Reyff and Ambaskar 2023) show that although there were high TL coefficients, the TL might have been lower had it been computed for a shorter range where Level A impacts occur.

Table 30. Comparison of the Extent of Sound Impacts in Meters Using Various DTH Driving Assumptions

Assumption	Marine Mammal						Fishes	
	Level A (Onset of AUD INJ)					Behavior	Injury	
	LF	HF	VHF	PW	OW	120 dB for Continuous Sounds	(>2 gm)	(>2 gm)
NMFS 2024	818	104	1266	727	271	13,594	25	25
DTH Report 2024	201	14	239	80	30	3,364	21	21

Assumptions: (1.) One pile, 240 minutes drilling/driving, 13 Hz strike rate, (2.) NMFS levels of 159 dB LE_{ss} and 167 dB L_{p,rms1s} at 10 m with TL coefficient of 15, spreadsheet default WFAs, (3.) DTH report levels of 156 dB LE_{ss} and 167 dB L_{p,rms1s} at 10 m with TL coefficient of 18.6, and average WFAs for 24-in piles, and (4.) Extent of impacts to marine mammals based on 2024 guidance.

DTH Drilling

Table 31 shows the extent of sound levels for the DTH drilling of typical tension anchor holes, similar to that shown for DTH driving in Table 30. Note that impacts to fish would not extend far from the activity (i.e., less than 10 m), because the LE_{ss} at 10 m would be below 150 dB.

Table 31. Comparison of the Extent of Sound Impacts in Meters Using Various DTH Drilling Assumptions

Assumption	Marine Mammal						Fishes	
	Level A (Onset of AUD INJ)					Behavior	Injury	
	LF	HF	VHF	PW	OW	120 dB for Continuous Sounds	(>2gm)	(>2gm)
NMFS 2024	109	14	169	97	36	2,512	<10	<10
DTH Report 2024	66	6	58	33	11	711	<10	<10

Assumptions: (1.) One pile, 240 minutes drilling/driving, 20 Hz strike rate, (2.) NMFS levels of 144 dB LE_{ss} and 156 dB Lp,rms_{1s} at 10 m with TL coefficient of 15, spreadsheet default WFAs, (3.) DTH report levels of 145 dB LE_{ss} and 155 dB Lp,rms_{1s} at 10 m with TL coefficient of 18.9, and average WFAs for 24-in piles, and (4.) Extent of impacts to marine mammals based on 2024 guidance.

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APPENDIX A – GLOSSARY OF TECHNICAL TERMS

Ambient sound – Normal background sound in the environment that has no distinguishable sources.

Ambient sound level – The background sound pressure level at a given location, normally specified as a reference level to study a new intrusive sound source.

Amplitude – The maximum deviation between the sound pressure and the ambient pressure.

Background level – Similar to ambient sound level with the exception that is a composite of all sound measured during the construction period minus the pile removal.

Continuous sound - A sound whose fluctuating sound pressure level remains above ambient sound during the event period (e.g., vibratory pile driving). In this report, non-impulsive sounds are considered continuous sounds.

Decibel (dB) – A customary scale most commonly used for reporting levels of sound. A difference of 10 dB corresponds to a factor of 10 in sound power. A unit describing the amplitude of sound, equal to 20 times the logarithm to the base 10 of the ratio of the pressure of the sound measured to the reference pressure. The reference pressure for water is 1 microPascal, and for air it is 20 microPascals (the threshold of healthy human auditory sensitivity).

Fast, Slow, and Impulse – Most sound level meters have two conventional time weightings, F = Fast and S = Slow with time constants of 125 milliseconds (ms) and 1,000 ms, respectively. Some also have I = Impulse time weighting, which is a quasi-peak detection characteristic with rapid rise time (35 ms) and a much slower 1.5-second decay.

- F = 125 ms up and down
- S = 1 second up and down
- I = 35 ms while the signal level is increasing or 1,500 ms while the signal level is decreasing.

Frequency – The number of complete pressure fluctuations per second above and below atmospheric pressure, measured in cycles per second (Hertz [Hz]). Normal human hearing is between 20 and 20,000 Hz. Infrasonic sounds are below 20 Hz and ultrasonic sounds are above 20,000 Hz.

Frequency spectrum – The distribution of frequencies that comprise a sound.

Hertz (Hz) – The units of frequency where 1 Hz equals 1 cycle per second.

Impulsive Sound – Transient sounds that are brief (less than 1 second) that are characterized by high peak sound pressure with rapid rise time and rapid decay. These sounds can occur in repetition (e.g., pile driving) or a single event (e.g., explosion). There is no definition of the repetitive rate that defines a sound as impulsive or continuous.

Kilohertz (kHz) – 1,000 Hz

Kurtosis – A measure of the variation of sound amplitude to reflect the impulsiveness of sound

A statistical quantity of kurtosis (β) is given by

$$\beta = \frac{T \cdot f_s \cdot \sum_{i=1}^N (p_i - \underline{p})^4}{\left[\sum_{i=1}^N (p_i - \underline{p})^2 \right]^2} \quad (7)$$

Where

f_s is the sampling frequency,

p_i is the instantaneous acoustic pressure, and

$\underline{p}$ is the arithmetic mean of p_i within the window duration T . For continuous Gaussian sound, $\beta_G = 3$.

L_{eq} – *Equivalent Average Sound Pressure Level (or Energy-Averaged Sound Level)*. The decibel level of a constant noise source that would have the same total acoustical energy over the same time interval as the actual time-varying noise condition being measured or estimated. L_{eq} values must be associated with an explicit or implicit averaging time in order to have practical meaning. The use of A-weighted, C-weighted, or Z-weighted (flat) decibel units sometimes is indicated by LA_{eq} , LC_{eq} , or LZ_{eq} , respectively.

LZ_{eq} – Z-weighted, L_{eq} , sound pressure level.

LZ_{max} – Maximum Sound Pressure level during a measurement period or a noise event.

LZ_{peak} – Z-weighted peak sound pressure level.

micropascal (μPa) – The Pascal (symbol Pa) is the SI unit of pressure. It is equivalent to one Newton per square meter. There are 1,000,000 microPascals in one Pascal.

Peak sound pressure level ($L_{p,pk}$) – The largest absolute value of the instantaneous sound pressure. This pressure is expressed in decibels (referenced to a pressure of 1 μPa for water and 20 μPa for air) or in units of pressure, such as μPa or Pounds per Square Inch.

Root mean square (RMS) sound pressure level (e.g., $L_{p,rms90\%}$, $L_{p,rms1s}$) – Decibel measure of the square root of mean square (RMS) pressure. For individual pulses, the average of the squared pressures over the time that comprise that portion of the waveform containing 90 percent of the sound energy of the impulse. To define continuous sources, a time constant of one second was used over the duration of activities.

SLM – Sound level meter.

Sound – Small disturbances in a fluid from ambient conditions through which energy is transferred away from a source by progressive fluctuations of pressure (or sound waves).

Sound exposure – The integral over all time of the square of the sound pressure of a transient waveform.

Sound exposure level or SEL (e.g., LE_{ss}, LE_{cum}) – The time integral of frequency-weighted squared instantaneous sound pressures. Proportionally equivalent to the time integral of the pressure squared. Sound energy associated with an acoustical event is characterized by the SEL. SEL is the constant sound level in one second, which has the same amount of acoustic energy as the original time-varying sound (i.e., the total energy of an event). SEL is calculated by summing the cumulative pressure squared over the time of the event ($1\mu\text{Pa}^2\text{-sec}$).

Sound pressure level (SPL) – An expression of the sound pressure using the decibel (dB) scale and the standard reference pressures of $1\mu\text{Pa}$ for water and $20\mu\text{Pa}$ for air when addressing human concerns. Sound pressure is the sound force per unit area, usually expressed in microPascals (or microNewtons per square meter), where 1 Pascal is the pressure resulting from a force of 1 Newton exerted over an area of 1 square meter. The SPL is expressed in dB as one or 20 times the logarithm to the base 10 of the ratio between the pressure exerted by the sound to a reference sound pressure. SPL is the quantity directly measured by a sound level meter.

Weighting Factor Adjustment (WFA) – Adjustments to sound levels based on marine mammal auditory weighting functions that focus on a single frequency. These adjustments are applied to the following marine mammal hearing groups: Low-frequency (LF) cetaceans, High-frequency (HF) cetaceans, Very high-frequency cetaceans, Phocid pinnipeds, and Otariid pinnipeds.

Z-Weighted – Z-weighting is a flat frequency response of 10 Hz to 20 kHz ± 1.5 dB. This response replaces the older "Linear" or "Unweighted" responses as these did not define the frequency range over which a sound level measurement would be linear.

A-Weighted - The sound pressure level in decibels as measured on a sound level meter using the A-weighting filter network. The A-weighting filter de-emphasizes the very low and very high frequency components of the sound in a manner similar to the frequency response of the human ear and correlates well with subjective reactions to noise.

APPENDIX B – SUMMARY OF DTH STUDIES

Study	Report Summary
<i>Assessment of Underwater Anthropogenic Noise Associated with Construction Activities in Bechers Bay, Santa Rosa Island, California</i> September 18, 2012 E. Dazey, McIntosh, B, S. Brown, K. Dudzinski	Measurements were conducted during marine pier demolition and reconstruction activities near Santa Rosa Island, California. This study described one of the methods as pneumatic percussion drilling methods for pile placement, which is assumed to be a DTH method. The study did not characterize the sound sources of each type of activity in a manner that sound levels for the various descriptors, peak, SEL, and RMS could be described for a given distance.
<i>Alaska DOT Hydroacoustic Pile Driving Noise Study – Comprehensive Report</i> November 23, 2016 S.L. Denes, G.J. Warner, M.E. Austin, and A.O. MacGillivray	This study included DTH sound measurements at the Kodiak ferry terminal in Alaska. Rock sockets were drilled, and the piles were set in the sockets with a vibratory hammer. Drilling occurred over a range of 40 min to 4 hours depending on the pile with most drilling occurring within one hour. This study included measurements from the installation of 8 piles. Water depths at the Kodiak ferry terminal were shallow (i.e., less than 10 m). Sound energy was broadband across the frequency spectra up to 10 kHz. Measurements for DTH rock sockets were made at distances of 10 to 1,136 m from the pile.
<i>Sound Source Verification, Down-hole Hammer Operation, August 13 & 15, 2018 - Vibratory Hammer Operation, August 15, 2018, Biorka Island Dock Replacement Project, Southeast Alaska</i> September 29, 2018 R. Miner. <i>And</i> <i>Underwater noise characterization of down-the-hole pile driving activities off Biorka Island, Alaska</i> June 24, 2020 S. Guan and R. Miner.	DTH measurements were conducted at Symonds Bay at a U.S. government facility on Biorka Island near Sitka, Alaska. Sound levels were measured from various pile installations that included vibratory driving and DTH drilling of 18-inch diameter open-end steel pipe piles. This study included measurements from the installation of 2 piles, although one ended early due to rough seas. Drilling occurred over 45 minutes for a partial pile and 90 minutes for a full pile. DTH sounds were not detected above background at 1,200 m. Measurements were made at 10 m for both piles but only one pile was measured at 200 m. These measurements made by Miner (2018) were reexamined and processed by Guan and Miner (2020) to report impulsive levels.
<i>Sound Source Characterization of Down-the-Hole Hammering Thimble Shoal, Virginia</i> October 3, 2019 Denes, S., Vallarta, J., and D. Zeddies 2019	Measurements of DTH hammering through rock were conducted at Thimble Shoal along the Chesapeake Bay Bridge Tunnel in Virginia (East Coast). Measurements were made for 5 piles, which two had an air bubble curtain in an attempt to reduce sound. Measurements were made at three fixed positions that were in a range of distances of about 10 m, 35 m, and about 75 m from the pile. This report demonstrated the impulsivity of the DTH sounds. The primary sound energy was between 100 and 1000 Hz. The use of a bubble curtain did not seem to show a clear reduction in sound levels; however, the frequency spectra was flattened slightly, suggesting the bubble curtain could be attenuating sound levels.
<i>White Pass & Yukon Railroad Mooring Dolphin – Pile Driving and Drilling Sound Source Verification</i> November 22, 2019 J. Reyff, Heyvaert, C. <i>And</i> <i>Review of Down-the-Hole Rock Socket Drilling Acoustic Data Measured for White Pass &</i>	This study included sound measurements at the cruise ship terminals near the Port of Skagway at the northern terminus of the Lynn Canal. Sound levels were measured for vibratory installation, impact driving, and DTH drilling of 42-inch diameter dolphin piles and DTH drilling of 8-inch diameter rock tension anchors. The piles were vibrated, then impact driven and finally drilled using DTH methods to their tip elevation in about 35-m-deep waters. Measurements included two 42-inch dolphin pile and two rock tensions anchors. Measurements for one of the DTH rock sockets were made at distances of 12, 100 and 1,400 m from the pile. Rock tension anchor DTH

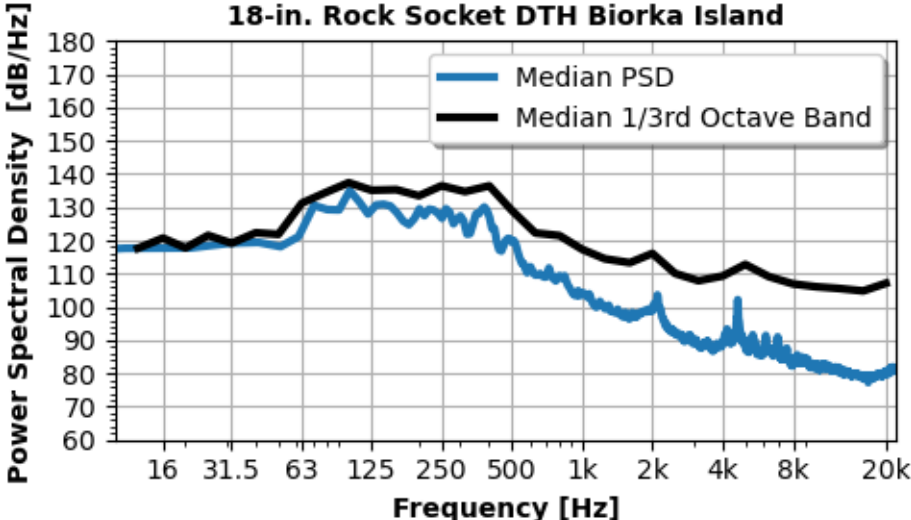
Study	Report Summary
<i>Yukon Route (WP&YR)</i> <i>Mooring Dolphins</i> May 28, 2020 J. Reyff	measurements were made at 22, 27, and 85 m for the first pile, 20, 85, and 700 m for a short period of the second pile, and 19, 85, and 110 m from the third pile. Sounds at 700 m were not measurable due to a combination of low amplitude source sounds and high background (rough seas). The original report considered the sound source to be where the percussive hammer interacted with the rock formations that are well below the water. A reanalysis by Reyff (2020) related sound levels to distance from the pile.
<i>Tenakee Ferry Terminal Improvements Project Pile Driving and Drilling Sound Source Verification, Tenakee Springs, AK</i> January 2021 C. Heyvaert and J. Reyff	This study measured sounds from pile driving and DTH rock sockets of various pile sizes and the DTH sounds from rock tension anchor installation. DTH measurements were conducted for three 24-inch diameter casings and six 8-inch rock tension anchor casings. The rock tension anchor measurements were divided into those for 24-piles and those for 18-inch piles, as levels were considerably different. DTH rock tension anchor sounds were considerably lower than the 24-inch rock casings. The sounds of rock anchors drilled within 18-inch piles was louder than rock anchors drilled within 24-inch piles. While the sounds had impulsive characteristics, the pulses were not distinctly above the constant drilling sounds and were not defined as impulsive.
<i>Auke Bay Ferry Terminal Modifications and Improvements Sound Source Verification Report</i> Auke Bay, AK July 22, 2021 Prepared by The Greenbusch Group, Inc. For Turnagain Marine Construction	This study measured sounds from DTH pile drilling of soil tension anchors for 24- and 30-inch diameter pile sizes. Measurements were made for the “soil anchors” of the 24 and 30-inch steel pipe piles. Each pile was driven in three segments). Measurements were made at distances of about 10 to 15 m out to 1,000 m from the pile. The sound levels reported are over the entire drilling process for each pile size in the study.
<i>Acoustic characteristics from an in-water down-the-hole pile drilling activity</i> Ketchikan, AK January 19, 2022 S. Guan, Brookens, T., Miner, R.	This paper describes underwater acoustic characteristics from DTH pile drilling during the drilling of 33-inch diameter (0.84 m) shafts for 48-inch (1.22 m) diameter steel piles at Ward Cove in Ketchikan, Alaska. Measurements were made over a range of 10 to 1,300 m. The sound levels measured in this study were lower than previous studies, and this sound was determined to be non-impulsive. The authors theorized that lower sound levels for this study were attributable to the lack of sound transmission from the percussive hammer to the pile. Unlike most other studies, most of the acoustic energy from this DTH pile drilling occurs had very low frequency content with much of the energy below 1 kHz.
<i>Underwater Measurements of Sound 610 mm OD Steel Pipe Piles, “Ring-Bit” Down-the-Hole Hammer October 31-November 5, 2022, Annette Island, AK - Metlakatla Seaplane Facility Refurbishment Project</i> Metlakatla, AK June 30, 2023 R. Miner	This study included sound measurements at the Metlakatla Seaplane Facility in Metlakatla Harbor on Annette Island, Alaska. DTH drilling sounds were measured for two 24-inch diameter steel piles. This study included measurements from the installation of 3 piles, although one ended very early due to complications and those results are not considered in this review. Measurements were made at 10 m, about 35 m, 140 to 150 m, and 1,000 m with roving measurements made at 135 to 525 m.
<i>2022 Monitoring Report for NOAA Fisheries Incidental Authorization (IHA) for Conclusion of Year Two P-310 IHA Activities and Preliminary Year One P-381 IHA ACTIVITIES</i>	This Project involved various marine construction activities that installed sheet piles, foundation piles, rock excavation (and borings), and mechanical rock removal. Methods included impact pile driving, vibratory installation, drilling, and rock hammering. Drilling DTH methods employed as part of this work for construction of a 78-inch diameter shaft, a 42-inch diameter shaft, and installation of 42-inch diameter casings. The intent of the measurement program was to measure at 10 m from activity; however, this was difficult to

Study	Report Summary
<i>from January 18, 2022, TO December 30, 2022, for Modification and Expansion of Dry Dock 1:</i> <i>Super Flood Basin (P-310) and Multifunctional Expansion of Dry Dock 1 (P-381)</i> Portsmouth Naval Shipyard, Kittery Maine April 14, 2023 NAVFAC	accomplish due to the congestion in the basin from barges and material for the various concurrent activities. Data interpretation and reporting includes extrapolations that will have to be reviewed further. Measurements were made for 10 instances of mechanical rock excavation being performed by a DTH mono-hammer utilizing a 42-inch diameter steel guide pile. However, only measurement data at 10 m for 4 events were found in the report. Measurements were also made at distant positions but those were influenced by obstructions and operation of an air bubble curtain.
<i>DTH Drilling Sound Source Verification - Gravina Freight and Gravina Airport Ferry Layup Facilities</i> Ketchikan, AK July 2023 J. Reyff, Ambaskar, A.	This study measured DTH sounds for rock socket driving for two 30-inch and two 24-inch rock sockets, along with sounds for DTH drilling of rock tension anchors at two different locations. Measurements were conducted at about 10 m, about 30 to 100 m, about 500 m, and about 1,000 m from the activity. There was considerable variability of sounds that were associated with issues in DTH drilling operations. DTH sounds were not clearly impulsive at distant positions. Note that levels reported for 24- and 30-inch piles were the loudest reported to date. One of the 24-inch piles was representative of a rare upset condition where the drill bit reportedly did not engage the bedrock properly and interacted with the pile. Therefore, the data for the two 24-inch. DTH driving events were reported separately.

APPENDIX C – SUMMARY OF DTH SOUND LEVELS BY PROJECT

DTH Driving Sounds

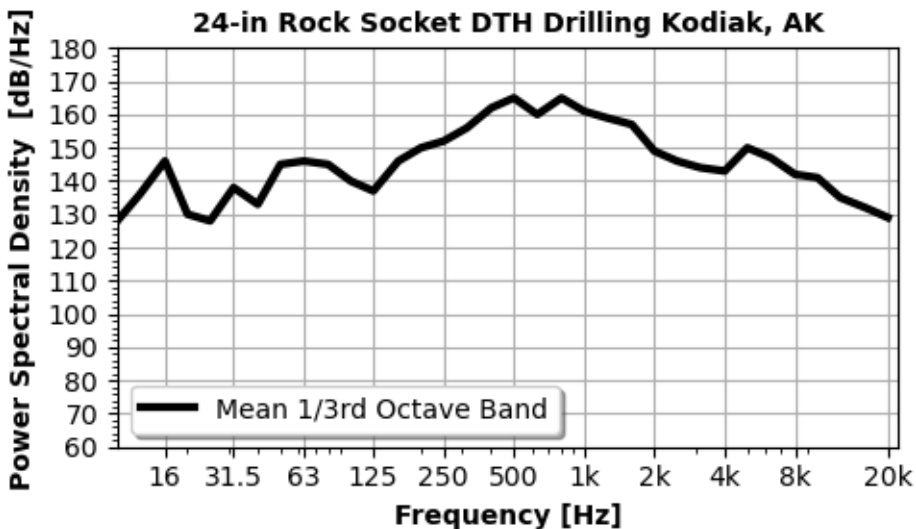
18-inch Rock Socket

Project: Biorka Island Dock Facility		Marine installation of 18-inch diameter mooring dolphin piles using vibratory driving and DTH drilling (Pile E14) Water depth: 3 to 4 meters		
DTH Activity:	Socket Piles	DTH Driving	18-inch dia. socket	
Duration:	~5,400 seconds	Rate = 13 Hz	~70,000 Pulses	
Range of Measurements¹		10 meters	200 meters	
Sound Pressure Levels at 10 meters (Median and Range)				
Median RMS (5-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
158 (156 to 158) dB ¹	146 (145 to 147) dB	162 (161 to 162) dB	172 (170 to 173) dB	
		0.03sec duration		
Transmission Loss				
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
-- ²	-- ²	-- ²	-- ²	
Frequency Weighting Factor Adjustments (at 10 meters)				
Cetaceans			Pinnipeds	
LF	HF	VHF	Otariid	Phocid
-2.8	-21.8	-31.5	-24.3	-15.4
Median 1/3rd Octave Band Level at 10 meters or near source level				
6.3				
8				
10				
12.5	118			
16	121			
20	118			
25	122			
31.5	119			
40	122			
50	122			
63	131			
80	134			
100	137			
125	135			
160	135			
200	133			
250	136			
315	135			
400	136			
500	129			
630	122			
800	121			
1000	117			
1250	114			
1600	113			
2000	116			
2500	110			
3150	108			
4000	109			
5000	113			
6300	109			
8000	107			
10000	106			
12500	106			
16000	105			
20000	107			

*Spectra for this project were provided by the author of the study in the form of narrowband data with a 10 Hz bandwidth. These were summed up according to the appropriate one-third octave band for the one-third octave band spectra

¹ Computed from SEL pulse level and hammer rate. ² Transmission loss not calculated since measurements only performed within 200 m. A measurement was made at 1,200 m but DTH sounds could not be quantified above background levels.

24-inch Rock Socket

Project: Kodiak, Alaska		Marine installation of 24-inch rock socket using DTH drilling at Kodiak, AK Water depth = 5 meters	
DTH Activity:	Rock Socket Piles	DTH Drilling	24-inch dia. anchors
Duration:	~2,700 to 13,200 seconds	Rate = 15.5 Hz	~41,850 to 204,600 Pulses
Range of Measurements		10 meters	~1,130 meters
Sound Pressure Levels (at 10 meters)			
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak
166 dB (156–171 dB)	154 dB ¹	NR	NR
		NR duration	
Transmission Loss			
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak
18.9	NR	NR	NR
Frequency Weighting Factor Adjustments (at 10 meters)			
Cetaceans		Pinnipeds	
LF	HF	VHF	Otariid Phocid
-0.3	-10.6	-23.3	-13.0 -5.5
Mean 1/3rd Octave Band Level at 10 meters or near source level			
6.3		24-in Rock Socket DTH Drilling Kodiak, AK 	
8			
10	128		
12.5	136		
16	146		
20	130		
25	128		
31.5	138		
40	133		
50	145		
63	146		
80	145		
100	140		
125	137		
160	146		
200	150		
250	152		
315	156		
400	162		
500	165		
630	160		
800	165		
1000	161		
1250	159		
1600	157		
2000	149		
2500	146		
3150	144		
4000	143		
5000	150		
6300	147		
8000	142		
10000	141		
12500	135		
16000	132		
20000	129		

¹ Not measured but estimated based on 10*Log(hammer rate).

NR – Not Reported

24-inch Rock Socket

Project: Tenakee Ferry Terminal Improvements Project		Marine installation of 24-inch Rock Socket dolphin piles using impact driving and DTH Drilling. Water Depth = 3 to 6 meters		
DTH Activity:	Socket Piles	Drilling	24-inch	
Duration:	~2,640 to 3,600 seconds	Rate = 9 Hz	~23,760 to 32,400 Pulses	
Range of Measurements		10 meters	1,100 meters	
Sound Pressure Levels (at 10 meters)				
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
167 dB (163-167) ¹	159 dB (154-158dB)	173 dB (169-174dB)	184 dB (183-184dB)	
		0.02 sec duration		
Transmission Loss				
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
19.1	19.4	20.3	19.8	
Frequency Weighting Factor Adjustments (at 10 meters)				
Cetaceans			Pinnipeds	
LF	HF	VHF	Otariid	Phocid
-2.9	-9.4	-16.9	-10.0	-7.7
Median 1/3rd Octave Band Level at 10 meters or near source level				
6.3	112			
8	134			
10	132			
12.5	120			
16	145			
20	145			
25	148			
31.5	147			
40	150			
50	150			
63	149			
80	150			
100	155			
125	159			
160	160			
200	158			
250	155			
315	150			
400	145			
500	145			
630	143			
800	143			
1000	143			
1250	141			
1600	141			
2000	142			
2500	145			
3150	139			
4000	141			
5000	141			
6300	140			
8000	137			
10000	136			
12500	132			
16000	129			
20000	125			

24-in. Rock Socket DTH Drilling Tenakee, AK

Power Spectral Density [dB/Hz]

Frequency [Hz]

Median PSD

Median 1/3rd Octave Band

*Spectra for this project was calculated from the most representative portions of the raw audio file captured during measurements made at Tenakee, AK.

¹ Computed based on 1-sec SEL and hammer rate.

24-inch Rock Socket

Project: Metlakatla Seaplane Facility, AK		Marine installation of 24-inch diameter steel piles using DTH hammer to advance piles into bedrock in Metlakatla Harbor, Annette Island, Alaska. Water depth = 9 to 12 meters, with 6-meter deep sockets		
DTH Activity:	Socket Piles	DTH Driving/Hammering	24-inch dia.	
Duration:	~400 to 3570 seconds	Rate = 9 to 11 Hz	~3,400to 39,270 Pulses	
Range of Measurements		10 meters	1,000 meters	
Sound Pressure Levels at 10 meters (Median and Range)				
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
165 (159 -170) ¹	155 (149-160) dB ¹	169 (163 - 174) dB ¹	180 (176 - 186) dB ¹	
		0.03 sec duration		
Transmission Loss				
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
15.5	15.5	15.7	15.9	
Frequency Weighting Factor Adjustments (at 10 meters)				
Cetaceans		Pinnipeds		
LF	HF	VHF	Otariid	Phocid
-1.4	-14.1	-27.5	-16.4	-9.0
Median 1/3rd Octave Band Level at 10 meters or near source level				
6.3				
8				
10				
12.5	121			
16	121			
20	124			
25	131			
31.5	136			
40	141			
50	143			
63	143			
80	142			
100	143			
125	144			
160	144			
200	145			
250	147			
315	150			
400	149			
500	149			
630	148			
800	144			
1000	141			
1250	142			
1600	139			
2000	136			
2500	137			
3150	133			
4000	131			
5000	129			
6300	128			
8000	124			
10000	122			
12500	121			
16000	119			
20000	115			

24-in. Rock Socket DTH Drilling Metlakatla, AK

Power Spectral Density [dB/Hz]

Frequency [Hz]

Median PSD

Median 1/3rd Octave Band

*Power Spectral density with a 1 Hz narrow bandwidth provided by author. One-third octave band spectra calculated from the power spectral density.

¹ Computed from regression of all measurements for all 3 measurement days.

24-inch Rock Socket

Project: Gravina Freight Facility		Marine installation of a 24-inch Rock Socket dolphin piles using vibratory driving and DTH Drilling. Water depth = 15 meters		
DTH Activity:	Socket Piles	Drilling	24-inch	
Duration:	~540 seconds	Rate = 14Hz	~7,500 Pulses	
Range of Measurements		10 meters	1,140 meters	
Sound Pressure Levels (at 10 meters)				
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
175 dB ¹	164 dB ¹	178 dB ¹	190 dB ¹	
		0.04sec duration		
Transmission Loss				
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
19.4	19.9	20.4	21.5	
Frequency Weighting Factor Adjustments (at 10 meters)				
Cetaceans			Pinnipeds	
LF	HF	VHF	Otariid	Phocid
-1.3	-14.0	-26.6	-16.4	-8.6
Median 1/3rd Octave Band Level at 10 meters or near source level				
6.3	112			
8	116			
10	118			
12.5	145			
16	149			
20	123			
25	135			
31.5	141			
40	145			
50	147			
63	155			
80	153			
100	151			
125	155			
160	162			
200	160			
250	163			
315	158			
400	159			
500	161			
630	162			
800	159			
1000	158			
1250	155			
1600	150			
2000	147			
2500	146			
3150	143			
4000	142			
5000	144			
6300	144			
8000	141			
10000	136			
12500	131			
16000	126			
20000	121			

24-in. Socket Pile DTH Gravina Freight Facility

Power Spectral Density [dB/Hz]

Frequency [Hz]

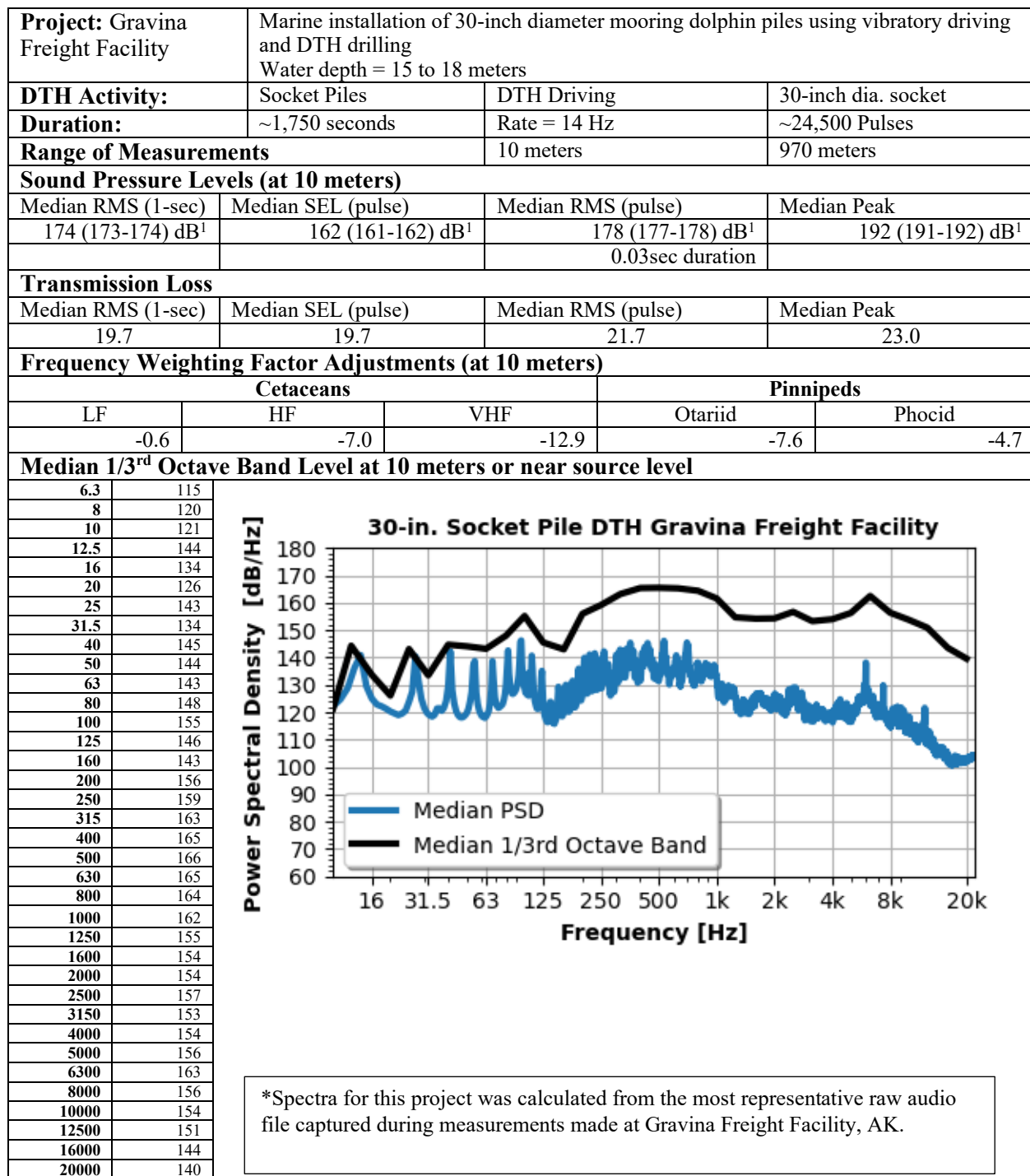
Median PSD

Median 1/3rd Octave Band

*Spectra for this project was calculated from the most representative raw audio file captured during measurements made at Gravina Freight Facility, AK.

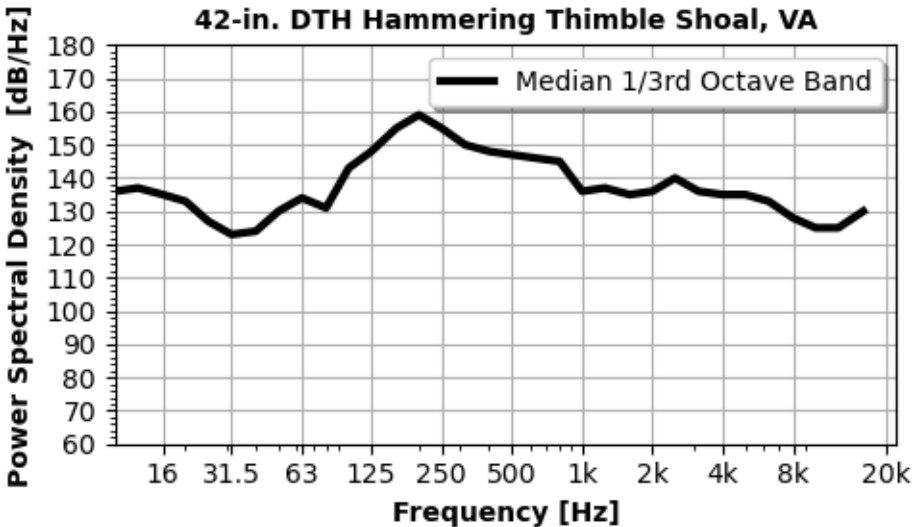
¹ Computed from regression of all measurements for the one measurement day.

30-inch Rock Socket



¹ Computed from regression of all measurements for the 2 measurement days.

42-inch Rock Socket

Project: Thimble Shoal Island, Virginia	Marine installation of 42-inch diameter piles using DTH hammering (Pile C10P4). Note that air bubble curtain used for project but not reflected in this evaluation of the data set. Air bubble curtain was not found to be noticeably effective. Depth not reported			
DTH Activity:	Socket Piles	DTH Driving/Hammering	42-inch dia.	
Duration:	~2,100 seconds	Rate = 7 Hz	~5,030 (4700-6800) Pulses	
Range of Measurements		10 meters	75 meters	
Sound Pressure Levels at 10 meters (Median and Range)				
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
172 (167 to 178) ¹	164 (159 to 170) dB	180 (175 to 186) dB	190 (185 to 197) dB	
		0.02 sec duration		
Transmission Loss				
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
-- ²	-- ²	-- ²	-- ²	
Frequency Weighting Factor Adjustments (at 10 meters)				
Cetaceans			Pinnipeds	
LF	HF	VHF	Otariid	Phocid
-1.4	-14.3	-29.5	-16.4	-9.8
Median 1/3rd Octave Band Level at 10 meters or near source level				
6.3				
8				
10	136			
12.5	137			
16	135			
20	133			
25	127			
31.5	123			
40	124			
50	130			
63	134			
80	131			
100	143			
125	148			
160	155			
200	159			
250	155			
315	150			
400	148			
500	147			
630	146			
800	145			
1000	136			
1250	137			
1600	135			
2000	136			
2500	140			
3150	136			
4000	135			
5000	135			
6300	133			
8000	128			
10000	125			
12500	125			
16000	130			
20000	122			

*Spectra for this project was digitized from the report directly for the most representative event. Narrow-band frequency data not available.

¹ Not Reported but calculated based on number of pulses per second.

² Transmission Loss not shown since the most distant measurement was 75 m.

42-inch Rock Socket

Project: White Pass & Yukon Railroad mooring, Skagway, AK		Marine installation of 42-inch diameter dolphin piles using impact, vibratory and DTH drilling. Water depth: 35 meters		
DTH Activity:	Socket Piles	DTH Drilling	42-inch dia. socket	
Duration:	~1,000 (603 to 1077) sec	Rate = 10 to 11 Hz	~6,040 to 6,644 Pulses	
Range of Measurements		12 meters	1,400 meters	
Sound Pressure Levels (at 10 meters)				
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
174 dB	164* dB	178 dB	194 dB	
		0.03 sec duration		
Transmission Loss				
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
16.2	16.2	--	16.7	
Frequency Weighting Factor Adjustments (at 12 meters from pile)				
Cetaceans			Pinnipeds	
LF	HF	VHF	Otariid	Phocid
-1.9	-17.8	-27.1	-19.3	-13.4
Median 1/3rd Octave Band Level at 10 meters**				
6.3		42-in. Rock Socket DTH Drilling WPYR Skagway, AK Power Spectral Density [dB/Hz] Frequency [Hz] Median PSD Median 1/3rd Octave Band		
8				
10	139.1			
12.5	118.6			
16	122.9			
20	141.4			
25	145.3			
31.5	144.0			
40	150.6			
50	155.0			
63	153.4			
80	158.1			
100	157.4			
125	161.3			
160	161.1			
200	164.4			
250	167.3			
315	165.3			
400	165.6			
500	165.1			
630	160.3			
800	153.0			
1000	152.3			
1250	153.4			
1600	157.6			
2000	158.3			
2500	151.9			
3150	148.6			
4000	146.4			
5000	143.5			
6300	140.0			
8000	136.7			
10000	132.3			
12500	128.1			
16000	127.5			
20000	128.6			

*Spectra for this project plotted from spreadsheets previously prepared by authors for the most representative event.

* Computed level from data set using hammering rate.

* Adjusted 10 m data from measurements made at 12 m.

42-inch Rock Socket

Project: Portsmouth Naval Shipyard, Kittery, ME		Marine installation of 42-inch diameter shafts via DTH mono hammer. Water depth = 10 – 13 meters		
DTH Activity:	Socket Piles	DTH Drilling	42-inch Socket	
Duration:	~475 to 1,711 seconds	Rate = 9 to 10 Hz	~4,275 to 17,110 pulses	
Range of Measurements		10 meters	188 meters	
Sound Pressure Levels (at 10 meters)				
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
164 (162 to 168) dB	155 (152-158) dB	167 dB ¹	181 (178 to 184) dB	
		0.06 sec duration		
Transmission Loss				
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
NR ²	NR ²	NR ²	NR ²	
Frequency Weighting Factor Adjustments (at 10 meters)				
Cetaceans			Pinnipeds	
LF	HF	VHF	Otariid	Phocid
-0.5	-8.8	-21.4	-10.1	-5.8
Median 1/3rd Octave Band Level at 10 meters or near source level				
6.3		42-in Steel Pile using DTH Mono-Hammer Portsmouth Naval Shipyard Kittery, ME — Median 1/3rd Octave Band		
8				
10				
12.5				
16				
20	144			
25	134			
31.5	130			
40	136			
50	139			
63	146			
80	152			
100	155			
125	155			
160	153			
200	166			
250	164			
315	170			
400	172			
500	175			
630	167			
800	158			
1000	157			
1250	158			
1600	158			
2000	167			
2500	168			
3150	166			
4000	158			
5000	157			
6300	153			
8000	151			
10000	146			
12500	143			
16000	137			
20000	140			

*Spectra for this project digitized directly from the daily monitoring reports for the pile installed on Sept 8, 2022, that was the most representative event. Narrow band data is plotted in the daily reports but was not plotted in this graphic.

¹ Based on SELss and pulse duration. RMS level reported appears to be based on 1 sec average time rather than pulse duration reported.

² NR: Not Reported. Note distant measurements had air bubble curtain between hydrophone and source.

DTH Drilling Sounds

8-inch Rock Tension Anchor Piles

Project: White Pass & Yukon Railroad mooring, Skagway, AK		Marine installation of 8-inch diameter rock tension anchors using DTH drilling (Pile MD4-SE) Water depth: 35 meters																										
DTH Activity:	Anchor Piles	DTH Drilling	8-inch dia. anchors																									
Duration:	~2,194 seconds	Rate = 15 Hz	~32,910 Pulses																									
Range of Measurements		19 meters	110 meters (and 600 meters) ¹																									
Sound Pressure Levels (at 10 meters)																												
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak																									
156 dB	144 dB ²	NA	<170 dB																									
		NA duration																										
Transmission Loss																												
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak																									
24.2	--	--	--																									
Frequency Weighting Factor Adjustments (at 19 meters)																												
Cetaceans			Pinnipeds																									
LF	HF	VHF	Otariid	Phocid																								
-1.3	-9.1	-19.4	-11.0	-5.2																								
Median 1/3rd Octave Band Level at 10 meters or near source level³																												
6.3		<table><tr><td>16</td><td>130.0</td></tr><tr><td>31.5</td><td>127.0</td></tr><tr><td>63</td><td>130.0</td></tr><tr><td>125</td><td>130.0</td></tr><tr><td>250</td><td>134.0</td></tr><tr><td>500</td><td>135.0</td></tr><tr><td>1000</td><td>139.0</td></tr><tr><td>2000</td><td>131.0</td></tr><tr><td>4000</td><td>126.0</td></tr><tr><td>8000</td><td>122.0</td></tr><tr><td>16000</td><td>121.0</td></tr><tr><td>20000</td><td>121.0</td></tr></table>			16	130.0	31.5	127.0	63	130.0	125	130.0	250	134.0	500	135.0	1000	139.0	2000	131.0	4000	126.0	8000	122.0	16000	121.0	20000	121.0
16	130.0																											
31.5	127.0																											
63	130.0																											
125	130.0																											
250	134.0																											
500	135.0																											
1000	139.0																											
2000	131.0																											
4000	126.0																											
8000	122.0																											
16000	121.0																											
20000	121.0																											
8																												
10	109.0																											
12.5	114.0																											
16	118.0																											
20	133.0																											
25	127.0																											
31.5	127.0																											
40	137.0																											
50	127.0																											
63	130.0																											
80	130.0																											
100	129.0																											
125	130.0																											
160	131.0																											
200	131.0																											
250	134.0																											
315	136.0																											
400	136.0																											
500	135.0																											
630	135.0																											
800	136.0																											
1000	139.0																											
1250	138.0																											
1600	136.0																											
2000	131.0																											
2500	131.0																											
3150	128.0																											
4000	126.0																											
5000	123.0																											
6300	124.0																											
8000	122.0																											
10000	120.0																											
12500	120.0																											
16000	121.0																											
20000	121.0																											

*Median 1/3rd octave band levels represent the median levels for the loudest and most representative event. Median PSD represents the calculated median sampled power spectral density for the loudest and most representative event. This data was obtained from the project spreadsheets.

¹ Measurements also made out to 600 m showed higher transmission loss. ² Computed from dataset using hammering rate. ³ Adjusted to 10 m. NA = not applicable since sound was not impulsive.

8-inch Rock Tension Anchor (for 18-inch diameter piles)

Project: Tenakee Ferry Terminal Improvements Project		Marine installation of 8-inch Rock Tension Anchors for 18-inch piles using impact driving and DTH Drilling. Water Depth = 5 to 6 meters		
DTH Activity:	Tension Anchor Piles	Drilling	8-inch	
Duration:	~879 to 915 seconds	Rate = 22 Hz	~19,338 to 20,130 Pulses	
Range of Measurements		10 meters	270 meters	
Sound Pressure Levels (at 10 meters)				
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
149 dB	NA	NA	164 dB	
		NA duration		
Transmission Loss (based on measurements to 270 meters)				
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
17.0	NA	NA	18.3	
Frequency Weighting Factor Adjustments (at 10 meters)				
Cetaceans			Pinnipeds	
LF	HF	VHF	Otariid	Phocid
-1.7	-13.1	-22.3	-14.6	-9.5
Median 1/3rd Octave Band Level at 10 meters or near source level				
6.3	103			
8	106			
10	100			
12.5	99			
16	104			
20	120			
25	113			
31.5	111			
40	122			
50	117			
63	125			
80	128			
100	129			
125	131			
160	135			
200	137			
250	137			
315	135			
400	131			
500	128			
630	127			
800	127			
1000	129			
1250	128			
1600	126			
2000	125			
2500	126			
3150	122			
4000	118			
5000	117			
6300	117			
8000	116			
10000	115			
12500	115			
16000	113			
20000	113			

8-in Tension Anchors for 18-in pile DTH Drilling Tenakee, AK

***Spectra for this project was calculated from raw audio file captured during measurements made at Tenakee, AK for the most representative event.**

NA: not applicable since sounds were treated as non-impulsive.

8-inch Rock Tension Anchor (for 24-inch diameter piles)

Project: Tenakee Ferry Terminal Improvements Project		Marine installation of 8-inch Rock Tension Anchors for 24-inch piles using impact driving and DTH Drilling. Water Depth = 3 to 6 meters		
DTH Activity:	Tension Anchor Piles	Drilling	8-inch	
Duration:	~400 to 900 seconds	Rate = 22 Hz	~8,734 to 19,800 Pulses	
Range of Measurements		10 meters	935 meters	
Sound Pressure Levels (at 10 meters)				
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
141 dB	NA	NA	155 dB	
		NA duration		
Transmission Loss				
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
19.2	NA	NA	17.9	
Frequency Weighting Factor Adjustments (at 10 meters)				
Cetaceans			Pinnipeds	
LF	HF	VHF	Otariid	Phocid
-2.4	-18.2	-28.0	-20.7	-12.6
Median 1/3rd Octave Band Level at 10 meters or near source level				
6.3	95	8-in Tension Anchors for 24-in pile DTH Drilling Tenakee, AK — Median PSD — Median 1/3rd Octave Band		
8	95			
10	95			
12.5	95			
16	96			
20	105			
25	107			
31.5	101			
40	112			
50	115			
63	125			
80	129			
100	133			
125	133			
160	134			
200	132			
250	129			
315	132			
400	130			
500	129			
630	127			
800	124			
1000	124			
1250	120			
1600	115			
2000	116			
2500	113			
3150	111			
4000	109			
5000	107			
6300	106			
8000	106			
10000	106			
12500	107			
16000	107			
20000	108			

*Spectra for this project was calculated from raw audio file captured during measurements made at Tenakee, AK for the most representative event.

NA: not applicable since not impulsive in far-field acoustical environment.

10-inch Soil Anchor

Project: Auke Bay Ferry Terminal, AK		Marine installation of a 10-inch diameter soil anchor for a 30-inch steel pipe pile using DTH drilling in 3 segments Water Depth: 39 meters		
DTH Activity:	Soil Anchor Piles	DTH Drilling	10-inch dia. anchors	
Duration:	~7,800 seconds	Rate = 17.5 Hz	~132,000 Pulses	
Range of Measurements		10 meters	1,000 meters ¹	
Sound Pressure Levels (at 10 meters)				
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
163 dB ²	151 dB	166 dB	184 dB	
		0.03 sec duration		
Transmission Loss				
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
17 ³	17 ³	18 ³	22 ³	
Frequency Weighting Factor Adjustments (at 10 meters)				
Cetaceans			Pinnipeds	
LF	HF	VHF	Otariid	Phocid
-0.1	-6.1	-24.0	-8.2	-2.5
Median 1/3rd Octave Band Level at 10 meters or near source level				
6.3		6 to 8-in. Soil Anchor DTH Drilling Auke Bay, AK Power Spectral Density [dB/Hz] Frequency [Hz] Median PSD Median 1/3rd Octave Band		
8				
10				
12.5	140			
16	129			
20	129			
25	129			
31.5	131			
40	131			
50	131			
63	134			
80	129			
100	132			
125	133			
160	140			
200	144			
250	145			
315	148			
400	146			
500	150			
630	153			
800	156			
1000	158			
1250	156			
1600	158			
2000	157			
2500	153			
3150	145			
4000	135			
5000	131			
6300	125			
8000	121			
10000	119			
12500	118			
16000	117			
20000	116			

*Spectra for this project was provided by the author in 20 Hz bandwidth. One-third octave band data was calculated from this 20 Hz bandwidth narrow band data.

¹ Data measured at 1,000 m cannot be clearly distinguished from background sound levels. ² Computed from SEL pulse level and hammer rate. ³ Transmission Loss computed using the far-field measurement level at or near background levels.

8-inch Tension Anchor

Project: Gravina Ferry Layup Facility		Marine installation of 8-inch Rock Tension Anchors using DTH Drilling Water depth = 15 meters		
DTH Activity:	Rock Tension Anchors	Drilling	8-inch	
Duration:	~3900 (3,500-4,500) sec.	Rate = 22Hz	~85,000 Pulses	
Range of Measurements		10 meters	1,000 meters	
Sound Pressure Levels (at 10 meters)				
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
157 dB (158-161dB) ¹	146 dB (145-148dB) ¹	162 dB (160-164dB) ¹	177 dB (174-179dB) ¹	
		~0.03 sec duration		
Transmission Loss				
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
17.1	NA	NA	22.6	
Frequency Weighting Factor Adjustments (at 10 meters)				
Cetaceans			Pinnipeds	
LF	HF	VHF	Otariid	Phocid
-0.3	-10.1	-30.0	-12.9	-5.0
Median 1/3rd Octave Band Level at 10 meters or near source level				
6.3	109			
8	115			
10	114			
12.5	119			
16	123			
20	128			
25	130			
31.5	121			
40	125			
50	122			
63	136			
80	134			
100	137			
125	133			
160	128			
200	136			
250	142			
315	142			
400	149			
500	150			
630	150			
800	151			
1000	150			
1250	147			
1600	147			
2000	142			
2500	135			
3150	131			
4000	131			
5000	125			
6300	110			
8000	101			
10000	99			
12500	98			
16000	97			
20000	98			

8-in. Tension Anchors DTH Gravina Airport Ferry Layup Facility

Power Spectral Density [dB/Hz]

Frequency [Hz]

Median PSD

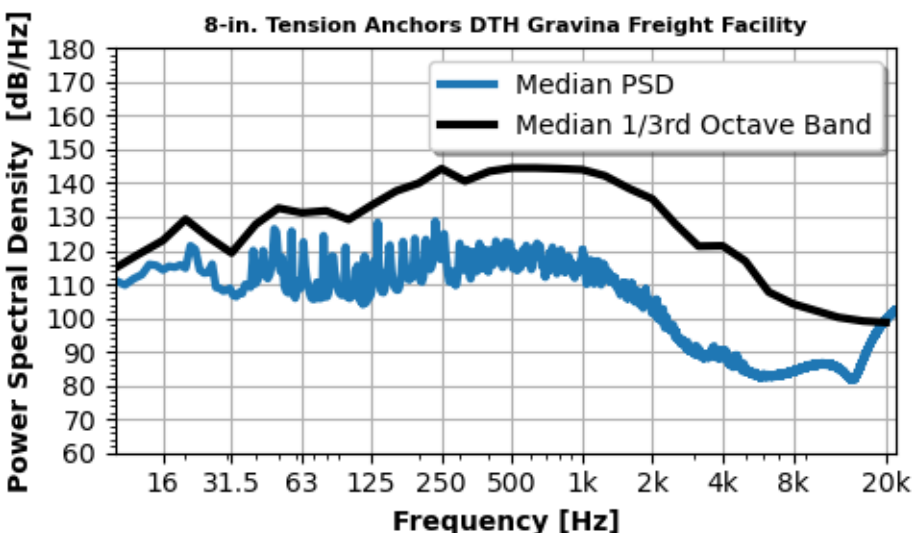
Median 1/3rd Octave Band

*Spectra for this project was calculated from raw audio file captured during measurements made at Gravina Ferry Layup Facility, AK for the most representative event.

¹ Based on regression analysis using all measurement points.

NA: not applicable since not impulsive in far-field acoustical environment.

8-inch Tension Anchor

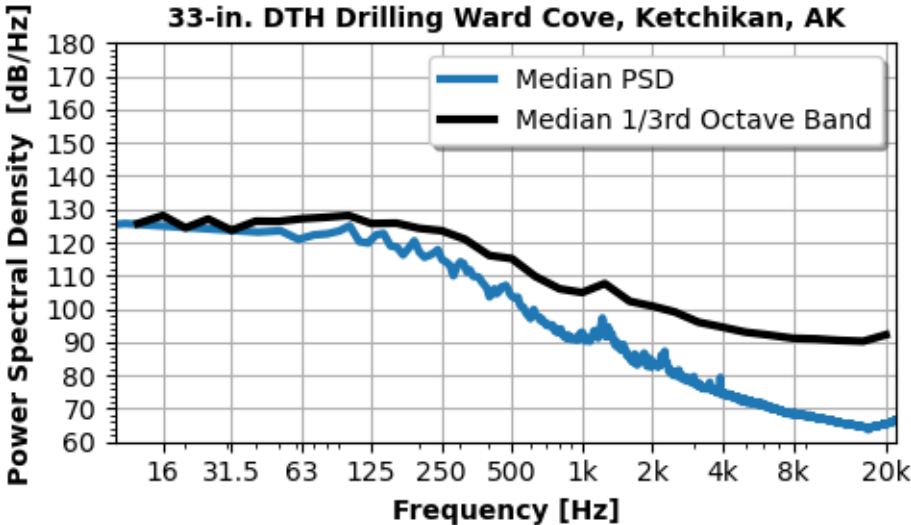
Project: Gravina Freight Facility		Marine installation of 8-inch Rock Tension Anchors using DTH Drilling Water depth = 20-25 meters		
DTH Activity:	Tension Anchors	Drilling	8-inch	
Duration:	~3,600 seconds	Rate = 22 Hz	~65,000 Pulses	
Range of Measurements		10 meters	910 meters	
Sound Pressure Levels (at 10 meters)				
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
155 dB (153-159dB) ¹	143 dB (141-147dB) ¹	156 dB (154-160dB) ¹	169 dB (166-173dB) ¹	
		0.05 sec duration		
Transmission Loss				
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
19.1	NA	NA	18.5	
Frequency Weighting Factor Adjustments (at 10 meters)				
Cetaceans			Pinnipeds	
LF	HF	VHF	Otariid	Phocid
-0.4	-11.7	-33.7	-14.8	-5.9
Median 1/3rd Octave Band Level at 10 meters or near source level				
6.3	106			
8	102			
10	104			
12.5	117			
16	119			
20	128			
25	124			
31.5	121			
40	131			
50	134			
63	131			
80	128			
100	128			
125	134			
160	139			
200	144			
250	145			
315	146			
400	147			
500	152			
630	151			
800	150			
1000	149			
1250	148			
1600	143			
2000	136			
2500	130			
3150	124			
4000	125			
5000	121			
6300	108			
8000	105			
10000	104			
12500	102			
16000	102			
20000	102			

*Spectra for this project was calculated from raw audio file captured during measurements made at Gravina Freight Facility, AK for the most representative event.

¹ Based on regression analysis using all measurement points.

NA: not applicable since not impulsive in far-field acoustical environment.

33-inch Rock Anchor

Project: Ward Cove, Ketchikan AK		Marine installation of 33-inch diameter (0.84 m) shafts for 48-inch (1.22 m) diameter steel piles via DTH drilling (June 19, 2020). Water Depth = ~30 meters		
DTH Activity:	Rock Anchor	DTH Drilling	33-inch Anchor	
Duration:	~8,820 seconds	Rate = 10 to 12 Hz	~88,200 to 105,840 pulses	
Range of Measurements		10 meters	1,300 meters ¹	
Sound Pressure Levels (at 10 meters)				
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
149 (147-151) dB	140 (138-142) dB	153 (150-155) dB	161 (158-163) dB	
		0.06 sec duration		
Transmission Loss				
Median RMS (1-sec)	Median SEL (pulse)	Median RMS (pulse)	Median Peak	
13.1 – 15.4 ¹	13.4-15.5 ¹	13.3-15.1 ¹	13.2-13.9 ¹	
Frequency Weighting Factor Adjustments (at 10 meters)				
Cetaceans			Pinnipeds	
LF	HF	VHF	Otariid	Phocid
-6.5	-28.3	-39.5	-31.0	-22.0
Median 1/3rd Octave Band Level at 10 meters or near source level				
6.3		33-in. DTH Drilling Ward Cove, Ketchikan, AK 		
8				
10				
12.5	126			
16	128			
20	124			
25	127			
31.5	124			
40	126			
50	126			
63	127			
80	128			
100	128			
125	126			
160	126			
200	124			
250	124			
315	121			
400	116			
500	115			
630	110			
800	106			
1000	105			
1250	108			
1600	102			
2000	101			
2500	99			
3150	96			
4000	95			
5000	93			
6300	92			
8000	91			
10000	91			
12500	91			
16000	90			
20000	92			

*Spectra for this project was provided by the author in 10 Hz bandwidth. One-third octave band data was calculated from this 10 Hz bandwidth narrow band data.

¹ Measurement made at 1,300 m did not include entire duration of DTH drilling event due to contamination from nearby vessel sound. Other measurements made within 200 m.

APPENDIX D - DTH MEASUREMENT PROTOCOL

[illegible]