7.0 Construction Noise Impact Assessment

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Chapter Summary

- The project biologist must analyze the extent of noise because it is one element used to define the action area.
- The project biologist must analyze the effects of noise on all animal species addressed in the BA.
- The two most common types of in-air noise based on attenuation dynamics are point source and line source.
- Natural factors such as topography, vegetation, and temperature can reduce in-air noise over distance. A hard site exists where noise travels away from the source over a generally flat, hard surface such as water, concrete, or hard-packed soil. When ground cover or normal unpacked earth is present between the source and receptor, the ground becomes absorptive to noise energy and is defined as a soft site.
- Topography, vegetation, and atmospheric factors can also affect the rate of noise attenuation.
- Existing sound levels can serve as a baseline from which to measure potential disturbance caused by project activities. Baseline sound is characterized as either background or ambient sound and levels vary greatly and depend on site-specific factors.
- Most transportation projects have traffic noise. Although traffic noise may seem to be the dominant background sound, in most cases, background sound levels exclusive of traffic are used to determine construction noise attenuation.
- One of the hardest things to quantify is noise associated with construction activities.
- Although noise from multiple sources at the same location results in louder levels than a single source alone, decibels are measured on a logarithmic scale, so noise levels cannot be added by standard addition.
- Defining the extent of project-related noise requires the following steps:

    1. Estimate the equipment noise level for the project.
    2. Estimate the background sound level.
    3. Estimate traffic noise.

4. Determine whether hard or soft site conditions exist.

5. Determine whether the construction noise is a point source or line source noise. It is usually considered point source.

- Use the correct equation to solve for the distance construction noise will travel before it attenuates to the background sound level. In some instances (for example, projects that are politically volatile or subjected to significant public scrutiny or those that occur in areas of extreme or highly variable topography), a project may require a more rigorous noise assessment for determining the extent of the action area.

- The Services provide threshold values for making effect determinations for some listed species. The threshold distances for in-air noise are defined as a known distance where noise at a given level elicits some response from a target species.

- Over long distances, water currents bend underwater noise waves upward when propagated into the current and downward downstream. Noise waves bend toward colder, denser water.

- Underwater noise levels are measured with a hydrophone, or underwater microphone, which converts sound pressure to voltage, expressed in Pascals (Pa), pounds per square inch (psi), or decibels (dB).

- Several different metrics are used to describe underwater noise:

- Peak pressure is the instantaneous maximum overpressure, or underpressure, observed during each pulse and can be presented in Pascals (Pa) or SPL in decibels (dB) referenced to a pressure of 1 micropascal (dB re: 1 µPa). When evaluating potential injury impacts to fish, peak sound pressure (dB_{peak}) is often used.

- The RMS level is the square root of the energy divided by the impulse duration. This level is the mean square pressure level of the pulse. NMFS uses RMS to describe disturbance-related effects (harassment) to marine mammals from underwater impulse-type noises.

- Sound Exposure Level (SEL) is also a metric for acoustic events and is often used as an indication of the energy dose. SEL is calculated by summing the cumulative pressure squared (p^2), integrating over time, and normalizing to 1 second. This metric accounts for both negative and positive pressures because p^2 is positive for both, and both are treated equally in the cumulative sum of p^2 (Hastings and Popper, 2005). The units for SEL are dB re: 1 μPa^2 sec.

- Transmission loss (TL) underwater is the accumulated decrease in acoustic intensity as an acoustic pressure wave propagates outward from a source. The intensity of the noise decreases with increasing distance due to spreading.
- Noise propagation factors in water include hydrographic conditions that affect noise transmission, such as currents or tides, sediment types, bottom topography, structures in the water, slope of the bottom, temperature gradient, and wave height.
- Existing underwater sound levels serve as a baseline from which to measure potential disturbance associated with project activities.
- In freshwater, broadband sound, in RMS should be used to represent the background noise level.
- In marine waters, use background sound levels that are representative of the frequency ranges heard by the functional hearing groups of marine mammals potentially present in the vicinity of the project. Choose the lowest frequency weighted background noise level to calculate the action area.
- When analyzing the extent of project-related noise, consider the area underwater through which the noise travels until it reaches background levels or encounters a land mass.
- The steps for defining the extent of project-related underwater noise are as follows:

    1. Determine the noise level for the project.
    2. Determine the background sound level. Remember to use broadband noise level for freshwater and the lowest frequency weighted background noise level for marine water.
    3. Determine applicable noise reduction factors. Use site- and attenuation device-specific data to represent anticipated attenuation. Consider analyzing scenarios for attenuation (high and low attenuation scenarios) that relate to the reported range of noise reduction measured for similar devices employed in similar site conditions.
    4. To determine the decrease in intensity of the noise away from the source, calculate noise attenuation at 4.5 dB per doubling of distance (Practical Spreading Model).
    5. Calculate the potential distance at which the project noise will attenuate to background levels, or encounter a land mass. In rivers,

sinuosity can truncate the area affected by elevated noise levels. Similarly, in marine environment, land masses can reduce the size of affected areas appreciably.

- For aquatic species, risk of injury or mortality resulting from noise is generally related to the effects of rapid pressure changes, especially on gas-filled spaces in the animal's body (such as swim bladder, lungs, sinus cavities, etc.).
- Generally, in-water or near-water pile driving is the issue of concern for the Services on WSDOT projects. If underwater blasting will occur, this should also be analyzed.
- Different aquatic species exhibit different hearing ranges, so the analysis should consider whether the frequency range of the activity overlaps with that of the species. Threshold distances and noise levels have been established to be used as a basis for effect determinations. These are the thresholds that should be used in your analysis of effects calculations:
- Marbled murrelet underwater thresholds: Auditory Injury – 202 dB SEL; Non-auditory Injury – 208 dB SEL. Guidance for behavioral effects – 150 dB_{RMS}.
- Marbled murrelet pile driving in-air masking area guidance for atypical projects in Puget Sound: 42 meters for steel piles 36-inch diameter and smaller, and 168 meters for steel piles greater than 36-inch diameter.
- Fish thresholds (salmon and bull trout) for Injury: > 2 grams – 187 dB cSEL; <2 grams – 183 dB cSEL; all sizes – 206 dB PEAK. For Behavioral effects – 150 dB_{RMS}.
- Marine mammals: Vibratory pile driving disturbance for Cetaceans and Pinnipeds – 120 dB_{RMS} or background sound, whichever is greater; impact pile driving disturbance for Cetaceans and Pinnipeds – 160 dB_{RMS}.
- In 2016, NMFS released acoustic injury thresholds for five marine mammal functional hearing groups (the guidance was revised in 2018, but the injury thresholds remain unchanged). There are dual injury thresholds (PEAK and cSEL) for impact driving. There is also a cSEL injury threshold associated with vibratory pile driving. NMFS has issued a spreadsheet to aid in the analysis of underwater noise effects on marine mammals that is available online at: https://www.fisheries.noaa.gov/national/marine-mammal-protection/marine-mammal-acoustic-technical-guidance
- NMFS has issued a spreadsheet to aid in the analysis of underwater sound effects on fishes that is available on-line at: http://www.wsdot.wa.gov/environment/technical/fish-wildlife/policies-and-procedures/esa-ba/noise

- USFWS has issued a spreadsheet to aid in the analysis of underwater sound effects on bull trout and diving marbled murrelets that is available on-line at the WSDOT website listed immediately above.

Noise from project activities can adversely affect wildlife in various ways. This chapter provides guidance on identifying construction-related noise and noise impacts in both terrestrial and aquatic settings. Basic acoustic concepts are covered, including noise generation, transmission, and reduction. Identifying background sound levels for comparison with anticipated project-related noise can assist the project biologist in more accurately identifying the extent of project-related noise and potential impacts on listed species.

The terms noise and sound should not be used interchangeably. *Noise* is characterized as <u>unwanted</u> sound, and because *ambient* and *background* sound are not considered adverse, they are not classified as noise. The ambient sound level is the total of all sound sources excluding anthropogenic sources. The background sound level is a composite of sound from all sources including anthropogenic sources. Ambient or background sound levels are the starting point for analyzing construction noise impacts such that the analysis measures and compares project-related noise to either ambient or background sound based on which best applies to existing site conditions. Most transportation projects will use background sound.

Three other terms used in this chapter are *source*, *path*, and *receiver*. The source is where a sound comes from, the path is the intervening terrain and factors that help to reduce the noise, and the receiver is the targeted recipient of the noise (such as human, eagle, microphone, etc.).

This discussion focuses on identifying the extent of project-related noise, which represents one element of the project action area, and the potential for noise impacts on wildlife. Noise transmission through air, and noise impacts on terrestrial species are addressed first. Next, underwater noise, sound pressure levels, and their effects on fish, diving marine birds, and marine mammals are discussed.

7.1 Terrestrial Noise

Noise is transmitted through air when an object moves, like water flowing over rocks, or air passing through vocal cords. This movement causes air waves, similar to ripples in water. When these waves reach an animal's ears, they are perceived as sound. Sound is measured in decibels. A decibel is a relative measure, not an absolute measure, that is accompanied by a reference scale ($dB = 20 * \log (P1/Pr)$, where P1 is the measured noise pressure and Pr is the reference pressure) to denote the Sound Pressure Level (SPL).

In-air noise when frequency-weighted to approximate human hearing is measured on an A-weighted scale, denoted as dBA.1 The A-weighted decibel scale begins at zero, which

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1 For sound pressure in air, the reference pressure is usually 20 micro-Pascal (μPa). One Pascal is the pressure resulting from a force of 1 newton exerted over an area of 1 square meter. Sound measured in air scale is referenced to 20 μPa in this document.

represents the faintest sound level that humans with normal hearing can hear. Decibels are measured on a logarithmic scale so each 10 dB increase doubles the sound; therefore, a noise level of 70 dBA is twice as loud to the listener as a noise of 60 dBA (USDOT 1995). Table 7-1 shows typical noise levels generated by common indoor and outdoor activities, and provides possible human responses.

Table 7-1. Typical noise levels and possible human responses.

Common Noises	Noise Level (dBA)	Effect
Rocket launching pad (no ear protection)	180	Irreversible hearing loss
Carrier deck jet operation Air raid siren	140	Painfully loud
Thunderclap	130	Painfully loud
Jet takeoff (200 feet) Auto horn (3 feet)	120	Maximum vocal effort
Pile driver Rock concert	110	Extremely loud
Garbage truck Firecrackers	100	Very loud
Heavy truck (50 feet) City traffic	90	Very annoying Hearing damage (8 hours of exposure)
Alarm clock (2 feet) Hair dryer	80	Annoying
Noisy restaurant Freeway traffic Business office	70	Telephone use difficult
Air conditioning unit Conversational speech	60	Intrusive
Light auto traffic (100 feet)	50	Quiet
Living room Bedroom Quiet office	40	Quiet
Library/soft whisper (15 feet)	30	Very quiet
Broadcasting studio	20	Very quiet
	10	Just audible
Threshold of hearing	0	Hearing begins

From: <http://www.nonoise.org/resource/educat/ownpage/soundlev.htm>.

7.1.1 Noise Generation, Transmission, and Reduction

7.1.1.1 Noise Sources

Noise is a pressure wave that decreases in intensity over distance from the source. Noise attenuation is described as a reduction in decibel level per doubling of distance from the source. Depending on the nature of the noise source, noise propagates at different rates. When reporting the noise level from a source, one should always specify the reference distance from the source for the sound measurement or estimated source. A standard reference distance for source noise levels is 50 feet. The two most common types of noise are point source and line source. These are discussed in more detail below.

Point Source Noise

Point source noise is usually associated with a source that remains in one place for extended periods of time, such as with most construction activities. A few examples of point sources of noise are pile drivers, jackhammers, rock drills, or excavators working in one location. However, noise from a single traveling vehicle is also considered a point source noise.

Construction point source noise is commonly measured by maximum decibel level (L_{max}), or the highest value of a sound pressure over a stated time interval (Harris 1991). Noise from a point source spreads spherically over distance. Think of this as a 3-dimensional model, where the wave spreading creates a dome effect, traveling in all directions equally from the source. The standard reduction for point source noise is 6 dB per doubling of distance from the source.

Line Source Noise

Line source noise is generated by moving objects along a linear corridor. Highway traffic is a good example of line source noise. When assessing line source noise levels the analyst should measure or estimate over longer time periods such as the L_{eq}(Equivalent Continuous Sound Level) rather than in maximum levels such as the L_{max} measured for point source noise. Only when noise comes from a very long continuous noise source such as a very long conveyor belt should the line source be represented by maximum event levels such as (L_{max}).

Noise from a line source spreads cylindrically, spreading outward along the length of a line. The standard reduction for line source noise is 3 dB per doubling of distance from the source (compared to 6 dB for construction point source noise).

Table 7-2 provides an example of noise attenuation of construction point and line source decibel levels based on distance from the source.

Table 7-2. Example of noise reduction over distance from a 95 dBA source showing variation between construction point source and line source.

	Noise Attenuation	
Distance from Source (feet)	Point Source (–6 dB)	Line Source (–3 dB)
50	95 dBA	95 dBA
100	89 dBA	92 dBA
200	83 dBA	89 dBA
400	77 dBA	86 dBA
800	71 dBA	83 dBA
1,600	65 dBA	80 dBA
3,200	59 dBA	77 dBA
6,400	53 dBA	74 dBA

7.1.1.2 Noise Path Reduction Factors

Natural factors such as topography, vegetation, and temperature can further reduce noise over distance. This section covers a few of the common factors and their applicability in increasing the noise reduction per doubling of distance from the source.

Hard Site versus Soft Site

A hard site exists where noise travels away from the source over a generally flat, hard surface such as water, concrete, or hard-packed soil. These are examples of reflective ground, where the ground does not provide any attenuation. The standard attenuation rate for hard site conditions is 6 dB per doubling of distance for point source noise and 3 dB per doubling of distance from line sources.

When ground cover or normal unpacked earth (a soft site) exists between the source and receptor, the ground becomes absorptive of noise energy. Absorptive ground results in an additional 1.5 dB reduction per doubling of distance as it spreads from the source. Added to the standard reduction rate for soft site conditions, point source noise attenuates at a rate of 7.5 dB per doubling of distance, and line source noise decreases at a rate of 4.5 dB per doubling of distance.

Topography, Vegetation, and Atmospheric Factors

A break in the line of sight between the noise source and the receptor can result in a 5 dB reduction. Dense vegetation can reduce noise levels by as much as 5 dB for every 100 feet of vegetation, up to a maximum reduction of 10 dB over 200 feet (USDOT 1995). Atmospheric conditions can also affect the rate of noise attenuation. Noise travels farther during periods of higher humidity and in colder temperatures (USFWS 2003). Wind can reduce noise levels by as much as 20 to 30 dB at long distances (USDOT 1995).

The influences of vegetation, topography, and atmospheric conditions as noise reduction factors can vary greatly so are difficult to include in an analysis. Therefore, these factors are generally not taken into account in environmental noise analyses over short distances. As a result, such analyses are conservative and likely to predict noise levels that are higher than actual noise levels.

7.1.2 Ambient or Background Sound Conditions

As defined for this manual, ambient sound level is the total of all sound sources in a specific area excluding anthropogenic sources. The background sound level is a composite of sound from all sources including anthropogenic sources. Normally the background sound level is selected as the baseline for evaluating construction noise impacts based on existing site conditions.

7.1.2.1 Existing Conditions

Determining background sound levels is the first step for a noise assessment. It can vary greatly depending on site-specific factors. Environmental factors can elevate background sound near the source, effectively hiding, or masking construction noise. The same environmental factors occurring near the receiver can change the receiver's perception of how loud construction noise is, or hide it completely.

Background and ambient sound levels vary by location even for undisturbed forested areas. WSDOT noise analyses on the San Juan Islands identified an ambient level of about 35 dBA, with regular noise intrusions from traffic and aircraft overflights ranging from 45 to 72 dBA (WSDOT 1994). A study on the Mt. Baker-Snoqualmie National Forest listed forested ambient levels between 52 and 60 dBA (USFS 1996). The environment surrounding transportation projects is often composed of high-speed highways, busy ferry terminals, and urban development. For projects occurring in these areas, background sound levels will include traffic noise and be much higher than that of a forested or undeveloped setting (see Section 7.1.4.1).

Weather conditions such as wind or rainfall can increase ambient sound in undeveloped areas. Locations near rivers or streams have higher ambient sound levels as well. As with the atmospheric conditions described above, environmental factors are so variable that models rarely take them into account.

The WSDOT project biologist should check with the WSDOT project manager to see if ambient or background sound data are available for the project or similar areas. If ambient or background information is not available and noise may be a major concern in the consultation, the biologist should have ambient or background sound within the project area measured by a professional.

7.1.2.2 Traffic Noise

The majority of projects assessed by a project biologist will include traffic noise. Identifying the amount and type of traffic helps to determine traffic noise. The level of highway traffic noise depends upon the traffic volume, the vehicle speeds, and the mix of trucks in the flow of traffic (USDOT 1995). Generally, the loudness of traffic noise is increased when traffic is heavier, when traffic speed is increased, and when a greater proportion of the traffic flow is heavy trucks.

For traffic volume, 2,000 vehicles per hour sounds twice as loud as (or is 10 dBA higher than) 200 vehicles per hour (USDOT 1995). For traffic speed, traffic at 65 miles per hour (mph) sounds twice as loud as traffic at 30 mph (USDOT 1995). In regard to the proportion of heavy truck traffic, one truck at 55 mph sounds as loud as 28 cars at 55 mph (USDOT 1995).

Vehicle noise comes from a combination of sources produced by engines, exhaust, and tires. The loudness of vehicle noise can also be affected by the condition and type of roadway, road grade, and the condition and type of vehicle tires.

Table 7-3 lists typical traffic noise levels for a variety of traffic volumes at various speeds, assuming 4 percent medium trucks, 6 percent heavy trucks, and a sound level modeled at 50 feet from the source. These numbers would be elevated as the percent of truck traffic volume increases. The State Highway Log can be used to find the posted speed for a state route. The Annual Traffic Report can be used to find the traffic volume, where traffic volume in vehicles per hour is equal to 10 percent of the Average Daily Traffic (ADT).

The State Highway Log is available at <http://www.wsdot.wa.gov/mapsdata/roadway/statehighwaylog.htm>; and the Annual Traffic Report is available at <http://www.wsdot.wa.gov/mapsdata/travel/annualtrafficreport.htm>.

7.1.3 Construction Noise

One of the easiest things for the project biologist to identify and one of the hardest things to quantify is noise associated with the actual construction of the project. How much noise will construction generate, how often will it occur, and how long it will last, are all questions that should be answered in the assessment. This section provides an introduction to equipment noise characteristics that the project biologist can use for typical construction projects.

Construction is usually performed in a series of steps or phases, and noise associated with different phases can vary greatly. However, similarities in noise sources allow typical construction equipment to be placed into one of three categories: heavy equipment, stationary equipment, or impact equipment.

Table 7-3. Typical noise levels for traffic volumes at a given speed.

Sound Level (dBA L_{eq} (hour)) at 50 feet

Volume (vehicles/hour) \ Speed (miles/hour)	35	40	45	50	55	60	65 / T60	65	70 / T60	70	75 / T60	75
125	57.3	58.5	59.7	60.9	62.0	63.1	63.8	64.1	64.5	65.1	65.2	66.1
250	60.2	61.4	62.6	63.8	64.9	66.0	66.7	67.0	67.4	68.0	68.2	69.0
500	63.2	64.4	65.6	66.8	67.9	69.0	69.7	70.0	70.4	71.0	71.2	72.0
1,000	66.2	67.4	68.6	69.8	70.9	72.0	72.7	73.0	73.5	74.0	74.2	75.0
2,000	69.2	70.4	71.6	72.8	73.9	75.0	75.7	76.1	76.5	77.0	77.2	78.0
3,000	71.0	72.2	73.4	74.6	75.7	76.8	77.5	77.8	78.2	78.8	79.0	79.8
4,000	72.2	73.4	74.6	75.8	76.9	78.0	78.7	79.1	79.5	80.1	80.2	81.0
5,000	73.2	74.4	75.6	76.8	77.9	79.0	79.7	80.0	80.4	81.0	81.2	82.0
6,000	74.0	75.2	76.4	77.6	78.7	79.8	80.5	80.8	81.2	81.8	82.0	82.8

T is the speed limit for truck traffic when it is posted differently from other vehicle traffic. For traffic volumes exceeding 6,000 per hour, add 1 dB for every 1,000 v/h increase at a particular speed.

7.1.3.1 Heavy Equipment

Analysts can categorize heavy equipment as earth-moving equipment, such as excavating machinery like excavators, backhoes, and front loaders, as well as materials handling equipment like graders, pavers, rollers, and dump trucks. Average maximum noise levels (L_{max}) at 50 feet from heavy equipment range from about 73 to 101 dBA for non-impact equipment (Table 7-4). These numbers were identified from several studies, and represent average maximum noise levels of reported values (FHWA 2011). During a phase of construction using heavy equipment, noise is generated more or less at a constant level. Therefore, noise levels can be quantified based on an average hourly level. Measurements collected on either side of mobile equipment moving in a liner path are referred to as Passby measurements. Measurements collected for stationary equipment that performs work in a repetitive cycle resulting in variations throughout the measurement period are referred to as Cyclical measurements.

Lacking onsite noise level data, the project biologist should use the worst-case scenario of the known equipment noise levels for a noise analysis. Manufacturers may also provide noise levels for their equipment, but the biologist must know the specific make and model of the equipment to be used for the project to obtain that information. Care should be taken to identify the distance at which the manufacturer has measured the equipment and ensure that the sound levels are provided as L_{eq} or L_{max} and not as a sound power level.

Table 7-4. Average maximum noise levels at 50 feet from common construction equipment.

Equipment Description[a]	Impact Device?	Actual Measured Average L_{max}[b] at 50 feet
Air-Operated Post Driver	Yes	83
Asphalt Distributor Truck (Asphalt Sprayer	No	70
Auger Drill Rig	No	70
Backhoe	No	84
Backup / Movement Alarm	No	80
Bar Bender	No	73
Blasting (rock slope production) [c]	Yes	126
Blasting (mitigated rock fracturing)	Yes	94
Boring Jack Power Unit [c]	No	83
Chain Saw	No	83
Chip Spreader	No	77
Clam Shovel (dropping) [c]	Yes	87
Compactor (ground)	No	75
Compressor (air)	No	68
Concrete Batch Plant	No	90
Concrete Grinder (Diamond Grinder)	No	97
Concrete Mixer Truck	No	82
Concrete Pump Truck	No	89
Concrete Saw	No	85
Crane	No	79
Directional Drill Rig	No	76
Dozer	No	86
Drill Rig Truck [c]	No	79
Drum Mixer	No	74
Dump Truck (Cyclical)	No	91
Dump Truck (Passby)	No	73
Excavator	No	87
Flat Bed Truck [c]	No	74
Front End Loader (Cyclical)	No	81
Front End Loader (Passby)	No	71
Generator	No	68
Generator (<25KVA, VMS signs) [c]	No	73
Gradall [c]	No	83
Grader (Passby)	No	79
Grapple (on backhoe)	No	87
Hoe Ram	Yes	97
Horizontal Boring Hydr. Jack	No	88
Impact Pile Driver	Yes	105
Jackhammer (Asphalt / Concrete)	Yes	95
Joint Sealer	No	74
Light Tower	No	63
Mud Recycler	No	74
Man Lift	No	75
Pavement Scarafier	No	84
Paving – Asphalt (Paver + Dump Truck)	No	82
Paving – Asphalt (Paver + MTV + Dump Truck)	No	83
Paving – Concrete (Placer + Slipform Paver)	No	91
Paving – Concrete (Texturing / Curing Machine)	No	74
Paving – Concrete (Triple Roller Tube Paver	No	89
Pickup Truck	No	75
Power Tools – Air Hose	No	98

Equipment Description[a]	Impact Device?	Actual Measured Average L_{max}[b] at 50 feet
Power Tools – Chipping Gun	No	101
Power Tools – Circular Saw (Cutting metal / wood)	No	77
Power Tools – Grinder (Grinding metal / concrete)	No	73
Power Tools – Hammer Drill	No	75
Power Tools – Impact Wrench	Yes	74
Power Tools – Jig Saw (Cutting steel)	No	95
Power Tools – Nail Gun	Yes	73
Power Tools – Reciprocating Saw (Cutting metal / wood)	No	66
Power Tools – Sander	No	69
Pumps	No	74
Refrigerator Unit [c]	No	73
Rivet Buster/chipping gun	Yes	107
Rock Drill	No	93
Roller	No	82
Rumble Strip Grinding (asphalt)	No	87
Sand Blasting (Single Nozzle)	No	103
Scraper	No	92
Shears (on backhoe)	No	96
Shot Crete 0Pump/Spray	No	86
Slurry Plant	No	78
Slurry Trenching Machine	No	80
Street Sweeper	No	81
Street Sweeper (Vacuum)	No	82
Telescopic Handler (Forklift)	No	88
Tractor [c]	No	84
Vacuum Excavator (Vac-truck)	No	87
Vacuum Street Sweeper [c]	No	82
Ventilation Fan	No	64
Vibrating Hopper [c]	No	87
Vibratory Concrete Mixer	No	80
Vibratory Pile Driver	No	105
Warning Horn	No	102
Water Jet Deleading [c]	No	92
Water Spray Truck	No	72
Welder / Torch	No	75

[a] NCHRP 25-49, 2018. Development of a Highway Construction Noise Prediction Model (Database) .

[b] L_{max} is the maximum value of a noise level that occurs during a single event.

[c] Construction Noise Handbook (FHWA, 2006).

7.1.3.2 Stationary Equipment

Stationary equipment such as pumps, power generators, and air compressors generally run continuously at relatively constant power and speeds. Noise levels at 50 feet from stationary equipment can range from 68 to 88 dBA, with pumps typically in the quieter range. The biologist can also assume an averaged noise level for stationary equipment because of its fixed location and constant noise pattern.

7.1.3.3 Impact Equipment

Impact equipment includes pile drivers, jackhammers, pavement breakers, rock drills, and other pneumatic tools where a tool bit touches the work. The noise from jackhammers, breakers, rock drills, and pneumatic tools comes from the impact of the tool against material. These levels can vary depending on the type and condition of the material. Noise levels at 50 feet from impact equipment, including pile drivers (Tables 7-5 and 7-6), jackhammers, and rock drills can range from 79 to 114 dBA. Blasting may be associated with impact equipment use and that noise can reach 126 dBA.

An impact pile-driving hammer is a large piston-like device that is usually attached to a crane. The power source for impact hammers may be mechanical (drop hammer), air steam, diesel, or hydraulic.

Table 7-4. Airborne sound levels for impact pile driving (A-weighted, dBA)

Location	Pile Diameter (in)	Water Depth (ft)	Hammer Type	A-weighted L_{Aeq}/RMS (dB)	Un-weighted L_{Aeq}/RMS (dB)	L_{max} (dBA)
Steel Pipe						
Coupeville Ferry Terminal[1]	30	30	APE	97	101	95
Coleman Ferry Terminal[2]	36	18	-	97	101	116
Mukilteo Ferry Terminal[3]	36	-	-	-	-	113
SR 520 Portage Bay[4]	24	23	-	78	-	106
Vashon Ferry Terminal[5,6]	24	12	-	96	-	108
	30	22	-	94	97	110
Concrete						
Coleman Ferry Terminal[2]	36 (hollow)	18	-	95	98	115
	18 (octagonal)	15	-	89	94	108
Mukilteo Ferry Terminal[3]	36 (hollow)	25	DelMag D62	-	-	111

Note: All measurement values are converted to a standardized measured distance of 50 feet.

-= no data

[1] Ghebreghzabiher, 2017.

[2] Soderberg and Laughlin, 2017.

[3] Laughlin, 2007.

[4] Illingworth and Rodkin, 2010.

[5] Soderberg, 2016.

[6] Soderberg and Laughlin, 2016.

Most impact pile driver hammers have a vertical support that holds the pile in place, and a heavy weight, or ram, moves up and down, striking an anvil that transmits the blow of the ram to the pile. In hydraulic hammers, the ram is lifted by fluid, and gravity alone acts on the down stroke.

A diesel hammer, or internal combustion hammer, carries its own power source and can be open-end or closed-end. An open-end diesel hammer falls under the action of gravity alone. A closed-end diesel hammer (double-acting) compresses air on its upward stroke and therefore can operate faster than open-end hammers.

Vibratory pile driver hammers are also used on projects. A vibratory pile-driving hammer has a set of jaws that clamp onto the top of the pile. The pile is held steady while the hammer vibrates the pile to the desired depth. Because vibratory hammers are not impact tools, noise levels are typically not as high as with impact pile drivers (Table 7-6). However, piles installed with a vibratory hammer must often be proofed, which involves striking the pile with an impact hammer to determine its load-bearing capacity, possibly with multiple impacts. The project biologist should check with the design engineer to determine if impact driving or proofing of the piles will be needed. If so, the project biologist should include proofing noise from impact pile driving in the assessment.

Table 7-5. Airborne sound levels for vibratory pile driving (A-weighted, dBA)

Location	Pile Diameter (in)	Water Depth (ft)	Hammer Type	A-weighted L_{Aeq}/RMS (dB)	Un-weighted L_{Aeq}/RMS (dB)	L_{max} (dBA)
Steel Pipe						
Vashon Ferry Terminal[1]	30	32	APE	80	-	88
Wahkiakum County Ferry Terminal[2]	18	11	DelMag D30-22	-	88	94
Coupeville (Keystone) Ferry Terminal[3]	30	30	APE	-	98	105
SR 520 Portage Bay[4]	24	23	-	98	-	105

Note: All measurement values are converted to a standardized measured distance of 50 feet.

[1] Ghebreghzabiher, 2017.

[2] Laughlin, 2010e.

[3] Laughlin, 2009.

[4] Illingworth and Rodkin, 2010.

Although stationary equipment noise and heavy equipment noise can be averaged over a period of time, impact pile driving noise consists of a series of peak events. Generally, noise from impact pile driving is reported at maximum levels. The loudest in-air noise from impact pile driving results from the impact of the hammer dropping on the pile, particularly when hollow steel piles are used. Noise levels will vary depending on pile type, size, substrate, and hammer type. Though noise levels are variable during pile driving, to be conservative (more protective of the listed species), the project biologist should assume that noise at the highest levels documented is generated by impact pile driving and should avoid using an average in a noise assessment.

When conducting an in-air noise assessment involving impact driving of hollow steel piles, determine if site-specific information is available. Noise assessments by WSDOT have documented maximum levels of 108 dBA L_{max} for 24-inch piles and 110 dBA L_{max} for 30-inch piles (Table 7-5). If site-specific information is not available, in-air noise levels associated with a particular sized pile can be obtained from Table 7-5.

When assessing in-air noise for pinnipeds, un-weighted Root Mean Square (RMS) sound level should be used to compare to the un-weighted RMS threshold values. Assessments by WSDOT have documented un-weighted RMS levels for a vibratory hammer to be between 88 dB (18-inch pile) and 98 dB (30-inch pile) at 50 feet (Laughlin 2010b). Un-weighted RMS impact hammer in-air sound levels were between 98 dB and 102 dB at 50 feet for 72-inch piles (Laughlin 2011).

Geotechnical investigations are a common activity associated with many transportation projects. Boring and coring are typically done with various drill rigs and driving hammers. Table 7-7 summarizes geotechnical investigation in-air noise levels measured at the Mukilteo Ferry Terminal.

Table 7-6. Airborne sound levels for geotechnical investigations (A-weighted, dBA)

Location	Activity	Water Depth (ft)	Distance (ft)	A-weighted L_{Aeq}/RMS (dB)	A-weighted L_{Aeq}/RMS @ 50 feet (dB)	L_{max} (dBA)	L_{max} @ 50 feet (dBA)
Mukilteo Ferry Terminal[1]	Hammering	45	124	68	72	75	79
	Drilling			65	69	65	69

Note: All measurement values are converted to a standardized measured distance of 50 feet.

[1] Gilbertson, 2007.

Blasting is another noise generating activity that should be assessed. Since blast noise typically is infrequent and of short duration, blast noise is generally assessed using a different noise metric than what is used for other more continuous types of noise. Blasting can occur in different situations and a variety of methods may be used. Due to the variability in blasting situations and techniques, noise from blasting is not fully addressed in this chapter. However, when blasting noise is part of a project, the project biologist should consider the following factors:

- Substrate – The location where blasting occurs partially determines the size of the charge and the duration of blasting. Blasting through bedrock requires more time and effort than blasting through less dense substrate.
- Size of charge – Blasting can use charges of less than a pound to over 200 pounds.

- Detonation system – Precision blasting may use a sequential delay system where each blast is subdivided into many smaller blasts, separated by a few milliseconds; or the blast may occur all at once.

- Directivity – Blasting above ground acts like point-source noise and spreads spherically from the source. Where blasting occurs below ground level, as in a shaft or pit, some directivity occurs, which directs the force of the blast upward more than horizontally, thereby lessening impacts.

- Use of BMPs – Best management practices may be used to lessen the energy of the blast. For example, when the charge is small enough, the use of heavy mats to cover the charge can significantly reduce the blast energy and contain any flying debris.

7.1.3.4 Rules for Decibel Addition

Once the project biologist can identify the type and level of construction equipment noise, it is important to discuss what happens when several pieces of equipment are operating at one time. Although noise from multiple sources at the same location results in louder levels than a single source alone, the decibel is measured on a logarithmic scale, so noise levels cannot be added by standard addition. Two noises of equal level (±1 dB) combine to raise the noise level by 3 dB. However, if two noises differ by more than 10 dB, there is no combined increase in the noise level; the higher output covers any other noise. The rules for decibel addition are shown in Table 7-8.

Table 7-7. Rules for combining noise levels.

When two decibel values differ by:	Add the following to the higher decibel value:
0 or 1 dBA	3 dBA
2 or 3 dBA	2 dBA
4 to 9 dBA	1 dBA
10 dBA or more	0 dBA

Source: USDOT (1995).

To determine the combined noise level of all construction equipment operating together, the project biologist should find the three pieces of equipment with the loudest noise levels, add the two lowest levels together using the rules of decibel addition as is shown in Table 7-8, then add the result to the third noise level using the same rules. For example: a project’s three loudest pieces of equipment have noise levels of 80, 79, and 70 dBA. Add the two lowest pieces of equipment using Table 7-8: 79 – 70 = 9; therefore 1 dBA is added to 79 dBA, resulting in a combined noise level of 80 dBA. Add 80 dBA to the next loudest piece of equipment: 80 – 80 is a difference of 0 or more; therefore 3 dBA is added to 80 dBA, resulting in a total noise level for all equipment combined of 83 dBA.

7.1.4 Determining the Extent of Project Related Noise

This discussion has introduced basic concepts and provided information on construction-related noise, traffic noise, and baseline sound levels. Using this information, the project biologist should be able to identify the extent of project-related noise, which constitutes one element defining the project action area. This section provides instructions for establishing the extent of noise and defining the noise element of the action area.

7.1.4.1 Determining the Background Sound Level

As part of the noise assessment, it is important to identify the background sound level throughout the area where construction noise is expected to extend. For transportation projects, traffic noise frequently exceeds the background sound level in the project area. However, in highly urbanized areas, other sounds may exceed traffic noise levels. Similarly, for projects in rural areas with little or no traffic, background sound levels also may not be defined by traffic noise.

Background sound levels vary depending on the level of development. Urban areas have the highest background sound levels, with daytime levels approximating 60 to 65 dBA (EPA 1978). Suburban or residential areas have background levels around 45 to 50 dBA (EPA 1978), while rural areas are the quietest with sound levels of 35 to 40 dBA (EPA 1978). Cavanaugh and Tocci (1998) identified typical urban residential background sound at around 65 dBA, high-density urban areas at 78 dBA, and urban areas adjacent to freeway traffic at 88 dBA. These sound levels may be important in a project noise assessment if traffic is absent near the project site or if construction noise extends beyond the extent of traffic noise. In this case, the project biologist can use Table 7-9, which lists daytime sound levels, exclusive of traffic, based on population density to determine the background sound level.

Table 7-8. Estimating existing environmental background noise levels.

Population Density (people per square mile)	L_{eq}[a] Daytime Noise Levels Exclusive of Traffic (dBA)
1-100	35
100-300	40
300-1,000	45
1,000-3,000	50
3,000-10,000	55
10,000-30,000	60
30,000 and up	65

Source: FTA (2006).

[a] Where L_{eq} is the *equivalent sound pressure level*: the steady noise level that, over a specified period of time, would produce the same energy equivalence as the fluctuating noise level actually occurring.

In urban and developed areas, traffic noise and construction noise attenuate (decline) to background in less distance than in undeveloped or rural areas. For example, it may take 2 miles or more for construction noise to reach background levels in a rural area, but the same noise may attenuate to urban background levels in less than a mile.

A general guideline is:

- If the distance where traffic noise attenuates to background levels is greater than the distance where construction noise attenuates to background levels, then the extent of construction noise is equal to the distance where construction noise attenuates to traffic noise levels. In this scenario, traffic noise from the roadway extends farther than construction noise. The extent of project noise is then calculated to where it attenuates to the traffic noise level, which is the dominant background sound. In this case, traffic noise is louder than background levels, and construction noise is audible until it attenuates to the same level as traffic noise.
- Conversely, if the distance where traffic noise attenuates to background levels is less than the distance where construction noise attenuates to background levels, then the extent of construction noise is equal to the distance where construction noise attenuates to background levels. In this case, construction noise extends farther than traffic noise from the roadway. The extent of project noise is then calculated to where it attenuates to the surrounding background levels. In this case, construction noise dominates until it attenuates to the same level as surrounding background sound.

Table 7-10 displays this relationship.

Table 7-9. Extent of project-related noise based on attenuation to the dominant background level.

If the distance noise attenuates:			The distance noise attenuates:			The distance of the extent of construction noise is based on attenuation:	
From	To		From	To		From	To
Traffic	Background	>	Construction	Background	Then	Construction	Traffic
Traffic	Background	<	Construction	Background	Then	Construction	Background

7.1.4.2 Equations for Solving Distances

Base 10-Log equations are used to 1) calculate noise levels at a specific distance from the source (such as construction noise levels at a nest located 650 feet from a project), 2) to determine the distance construction noise will travel before it attenuates to the traffic noise level, and 3) to determine the distance at which construction or traffic noise will attenuate to background sound levels.

Distance Construction Noise Attenuates to Ambient or Background

To determine the distance point source construction noise will travel before it attenuates to the ambient sound level; the following equation should be used:

$$\mathbf{D = Do * 10^{((Construction\ Noise\ –\ Ambient\ Sound\ Level\ in\ dBA)/\alpha)}}$$

Where D = the distance from the noise source
D_o = the reference measurement distance (50 feet in this case)
α = 25 for soft ground and 20 for hard ground. For point source noise, a spherical spreading loss model is used. These alpha (α) values assume a 7.5 dBA reduction per doubling distance over soft ground and a 6.0 dBA reduction per doubling distance over hard ground.

Example *– Project-related noise is estimated at 84 dBA, with 40 dBA for ambient sound in a forested site (soft site). At what distance will construction noise attenuate to the ambient sound level over soft ground?*

$D = D_o * 10^{((Construction\ Noise\ –\ Ambient\ Sound\ in\ dBA)/\alpha)}$
D_o = the reference measurement distance (50 feet in this case)
$D = 50 * 10^{((84 – 40)/25)}$
$D = 50 * 10^{(44/25)}$
$D = 50 * 10^{(1.76)}$
$D = 50 * 57.54$
D= 2,877 feet (about 0.5 miles)

Distance Traffic Noise Attenuates to Ambient or Background

To determine the distance line source traffic noise will travel before it attenuates to the ambient sound level, the following equation should be used:

$$\mathbf{D = Do * 10^{((Traffic\ Noise\ –\ Ambient\ Sound\ Level\ in\ dBA)/\alpha)}}$$

Where D = the distance from the traffic noise
D_o = the reference measurement distance (50 feet in this case)
α = 15 for soft ground and 10 for hard ground. For line source noise, a cylindrical spreading loss model is used. These alpha (α) values assume a 4.5 dBA reduction per doubling distance over soft ground and a 3.0 dBA reduction per doubling distance over hard ground.

Example *– Project-related noise is estimated at 84 dBA, and traffic noise is estimated at 66 dBA with 40 dBA for ambient sound in a forested site (soft site). At what distance will traffic noise attenuate to the ambient sound level over soft ground?*

$D = D_o * 10^{((Traffic\ Noise\ –\ Ambient\ Sound\ in\ dBA)/\alpha)}$
D_o = the reference measurement distance (50 feet in this case)
$D = 50 * 10^{((66 – 40)/15)}$
$D = 50 * 10^{(69/15)}$
$D = 50 * 10^{(1.733)}$

*D = 50 * 53.703*
D= 2,685 feet (0.5 miles)

<u>*Distance Construction Noise Attenuates to Traffic Noise*</u>

To determine the distance point source construction noise will travel before it attenuates to the traffic noise level; the following equation should be used:

$$\mathbf{D = Do * 10^{((Construction\ Noise\ –\ Traffic\ Noise\ in\ dBA)/\alpha)}}$$

Where D = the distance from the noise source
D_o = the reference measurement distance (50 feet is the standard)
α = 10. For the equation where you have Construction Noise – Traffic Noise in dBA / alpha; alpha will always be 10. The reason is that construction noise will be 20 for a point source over hard ground or 25 for a point source over soft ground and traffic is a line source which is 10 for hard ground or 15 for soft ground. When you subtract the two, the result is either 25-15 = 10 or 20-10=10. Either way it will always be 10.

Example *– Project-related noise is estimated at 84 dBA, and traffic noise is estimated at 66 dBA in a forested site (soft site). At what distance will construction noise attenuate to the same level as traffic over soft ground?*

$D = D_o * 10^{((Construction\ Noise\ –\ Traffic\ Noise\ in\ dBA)/\alpha)}$
D_o *= the reference measurement distance (50 feet in this case)*
$D = 50 * 10^{((84 – 66)/10)}$
$D = 50 * 10^{(18/10)}$
$D = 50 * 10^{(1.8)}$
*D = 50 * 63*
D= 3,154 feet (0.6 miles)

<u>*Construction Noise Levels at a Specific Distance*</u>

To determine construction noise levels at a specific distance, the following equation should be used:

$$\mathbf{L_{max} = Construction\ L_{max}\ at\ 50\ feet – 25 * Log(D/D_o)}$$

Where L_{max} = highest A-weighted sound level occurring during a noise event during the time that noise is being measured.
At 50 feet = the reference measurement distance (standard is 50 feet)
D = the distance from the noise source
D_o = the reference measurement distance (50 feet in this case)

***Example** – Project-related noise is estimated at 84 dBA, and traffic noise is estimated at 66 dBA in a forested site (soft site). A spotted owl nest is located 650 feet from the project. What is the expected construction noise level at the nest site?*

L_{max} *= Construction* L_{max} *at 50 feet – 25 * Log(D/*D_o*)*
Where L_{max} *= 84 dBA*
D = 650
D_o *= the reference measurement distance (50 feet in this case)*

L_{max} *= 84 dBA at 50 feet – 25 * Log(650/50)*
L_{max} *= 84 dBA at 50 feet – 25 * Log(13)*
L_{max} *= 84 dBA at 50 feet – 27.85*
L_{max} *= 56.15 dBA*

7.1.4.3 Steps for Defining the Extent of Project-Related Noise

The following subsection provides instructions for performing a noise assessment to determine the extent of project-related noise defining the action area. Remember that noise is just one element of the project that must be considered when determining the action area. See Chapter 8 for guidance on other elements that should be considered.

The following information is provided in a step-by-step format with an accompanying example project. The noise assessment outlined below is appropriate for the vast majority of WSDOT projects.

1. **Estimate the equipment noise level for the project**. To estimate the noise level of project activities, it is imperative to know and understand all equipment that will be used for the specific project. The project biologist should avoid assuming the types of equipment that may be used and ask the project design or engineering office for specific information. Once all project equipment is known, use the decibel levels for common construction equipment found in Table 7-4. This table shows the noise range for similar construction equipment. If specific noise levels are not known, take the noise level shown for at least the three noisiest pieces of equipment listed in the table. Remember to use the rules of decibel addition for the final project noise level. This method provides a conservative estimate, since not all equipment will be operating at the same time and location in most cases.

   ***Example** – The equipment used will be an excavator, heavy trucks, finish grader, and paver. The estimated worst-case scenario noise level for the construction equipment is: excavator, 81 dBA; dump trucks, 76 dBA; and paver, 77 dBA. The two pieces of equipment producing the least noise (dump truck at 76 dBA, and paver at 77 dBA) are added together for a difference of 1. Using the rules for decibel addition (see Table 7-8), add the 3 decibels to the highest value between the two (paver at 77 dBA) to get 80 dBA. Continuing* *with the rules of decibel addition, add 3 dBA to the piece of equipment with the highest noise level, the excavator at 81 dBA. Therefore, construction noise can be assumed to not exceed 84 dBA at 50 feet.*

2. **Estimate the background community or ambient sound level.** In more remote locations, background or ambient sound conditions are likely lower than traffic noise (see Section 7.1.2.1). In urban areas, community background sound may be greater than traffic noise, such as adjacent to airports. For many WSDOT projects, traffic noise will define the background sound level (see Step 3 below). By using the information in Section 7.1.4.1, it is possible to estimate the community background sound level for the project area, based on population density.

   Example *– The project is located on SR 101 in the vicinity of MP 216 in an undeveloped forested area. Based on the Olympic National Forest programmatic biological assessment, estimated ambient sound levels for undisturbed forested areas is 40 dBA (USFWS 2003).*

3. **Estimate the traffic noise level.** A noise discipline report may be available and contain project specific traffic noise levels. If one is not available the information in Section 7.1.2.1, can be used to estimate the traffic noise level for the project area by assessing traffic. The project biologist should define the ADT and the speed limit in the project area. If the ADT and speed limit are not obvious, consult the Annual Traffic Report (<http://www.wsdot.wa.gov/mapsdata/travel/annualtrafficreport.htm>) and the Washington State Highway Log (<http://www.wsdot.wa.gov/mapsdata/roadway/statehighwaylog.htm>), respectively, for information. Take 10 percent of the ADT to find the approximate worse case number of vehicles per hour. Use the closest fit from Table 7-3 for vehicles per hour and speed to estimate the decibel level of traffic in the project area. Remember that seasonal use of the roadway and the amount of heavy truck traffic can raise or lower typical noise levels. If your project does not fit Table 7-3 or there are significant topographic features in the area, then the project biologist should contact the WSDOT project office they are working with to ask if any acoustical monitoring has occurred in the project vicinity or in similar areas.

   Example *– The project is located on SR 101 in the vicinity of MP 216 in an undeveloped forested area. The speed limit in the project area is 60 mph; traffic levels will be elevated due to seasonal use and will include heavy truck traffic. The Annual Traffic Report lists the ADT on SR 101 at MP 216 at 2,000 vehicles per day. Therefore, vehicles per hour (vph) can be estimated as 10 percent of 2,000 or approximately 200 vph. Table 7-3 lists the noise level as*

66 dBA for a roadway with 250 vph and a 60 mph traffic speed, which is the best fit for the example.

4. **Determine whether hard or soft site conditions exist.** Section 7.1.1.2 describes the difference between hard and soft site conditions. A hard site exists where noise travels away from the source over a generally flat, hard surface such as water, concrete, or hard-packed soil. When ground cover or normal unpacked earth exists between the source and receptor, the ground becomes absorptive to noise energy and soft site conditions are present. Most project areas, other than sites adjacent to water or in developed areas having more than 90 percent concrete or asphalt, exhibit soft site conditions. For soft site conditions, add 1.5 dBA to the standard reduction factor.

    Example *–Based on the location of the project in a forested setting, it can be assumed that soft site conditions exist. Therefore, add the additional 1.5 dBA reduction to the standard reduction factors.*

5. **Determine whether the noise is point source or line source.** Use Section 7.1.1.1 to determine whether construction noise and traffic noise are point or line source. Typically, construction noise has a point source, regardless of the activity. Even moving projects such as pavers attenuate noise in point source dynamics. Although construction activity may move, the noisy activity typically remains in one location.

    If multiple noisy activities are occurring at different locations throughout the project area, the extent of project-related noise should be described at each location. For example, pile driving could be occurring at one location in the project corridor, while pavement grinding or rock drilling may be occurring elsewhere.

    Traffic noise is almost always line source noise. The standard attenuation rate for point source noise is 6 dBA, and the standard attenuation rate for line source noise is 3 dBA. These standard attenuation rates do not take into account any reduction factors, such as soft site, vegetation, or atmospheric conditions.

    Example *– All work on the project will occur at one location, and is considered point source noise. Therefore, adding the reduction for soft site conditions, construction noise will attenuate at a rate of 7.5 dBA per doubling of distance. Traffic noise (line source) will attenuate at a rate of 4.5 dBA per doubling of distance. This attenuation rate includes the 1.5 dBA reduction for soft site conditions.*

Use the equations for solving distances. Base 10-Log equations are used to calculate noise levels at a specific distance from the source, to determine the distance construction noise will travel before it attenuates to the traffic noise level, and also to determine the distance at which construction or traffic noise will attenuate to background sound levels.

Example with equations for solving for distance *– Project-related noise is estimated at 84 dBA, traffic noise is estimated at 66 dBA, and 40 dBA is estimated for ambient sound level. Using the equation in Section 7.1.4.2 the distance construction noise attenuated to ambient levels was to 2,877 feet. Using the equation in Section 7.1.4.2 for a line source noise, the distance traffic noise attenuated to ambient levels was 2,685 feet. In this example project, the extent of project-related noise is 2,877 feet. This is only slightly farther than traffic noise extends before attenuating to ambient levels (40 dBA). Therefore, at approximately 2,700 feet, traffic noise is not distinguishable from ambient sound levels and at approximately 2,900 feet construction noise is not distinguishable from ambient sound levels. Therefore, the extent of project generated noise is approximately 2,900 feet.*

If, in the example, traffic noise was high enough to extend past 2,900 feet, then the extent of project generated noise would be to where construction noise and traffic noise attenuated to the same level, but was still above the overall ambient level.

If the project occurs in a developed area, where other background sound exceeds traffic noise, the biologist can also use known background sound levels associated with the level of development, and determine when construction noise drops below the development level to identify the extent of project-related noise.

The distance calculated using the noise assessment method described above is a worst-case scenario and does not take into account naturally occurring ambient sounds such as water and wind, or topography, which can physically block noise.

Examples of two projects that might warrant a more detailed noise assessment are provided below, along with the subsequent extent of noise impacts that was calculated for each.

The first example is a blasting project. If blasting occurs along a small portion of the project corridor where work would occur, it would be most effective to develop a composite noise assessment with one element that evaluated noise generated by blasting activities and a second element that evaluated noise generated by other construction activities. This would require the biologist to complete at least two noise assessments to effectively characterize these different elements. The area influenced by blasting noise would be substantially larger than the area affected by routine construction activities and equipment. Therefore, a larger radius would define the extent of noise surrounding the blasting activities than the radius defining the extent of noise from other activities. As a result, the noise component of the action area defined for the project would display a larger circle of anticipated noise effects around blasting activities than is exhibited around the remaining corridor.

A second example of a project requiring a more detailed noise assessment is a project corridor that is surrounded by both hard and soft site conditions. For those areas surrounding the road that possess soft site characteristics, the biologist would calculate the extent of noise that is generated by proposed construction activities and equipment using an attenuation rate for soft site conditions. For those areas surrounding the road that possess hard site characteristics, the biologist would calculate the extent of noise that is generated by proposed construction activities and equipment using an attenuation rate for hard site conditions. The extent of anticipated noise impacts in soft site areas would be smaller in area than the extent that is exhibited in hard site areas. As a result, the noise component of the action area defined for the project would display a larger radius of anticipated noise effects in hard site areas than is exhibited around the remaining soft site segments of the project corridor.

There may be some specific projects that warrant a more rigorous noise assessment than is described in the procedure or outlined in the examples provided above. For example, the blasting activities described above could take place in a canyon, where surrounding topography would inhibit the transmission of noise to surrounding areas or confine noise impacts to a smaller area. For these projects, the WSDOT project manager may request that a project biologist work with WSDOT noise specialists to develop a more sophisticated analysis. Figure 7-1 below illustrates the variation in the extent of noise impacts stemming from different project activities (paving vs. blasting) as well as variation in surrounding topography.

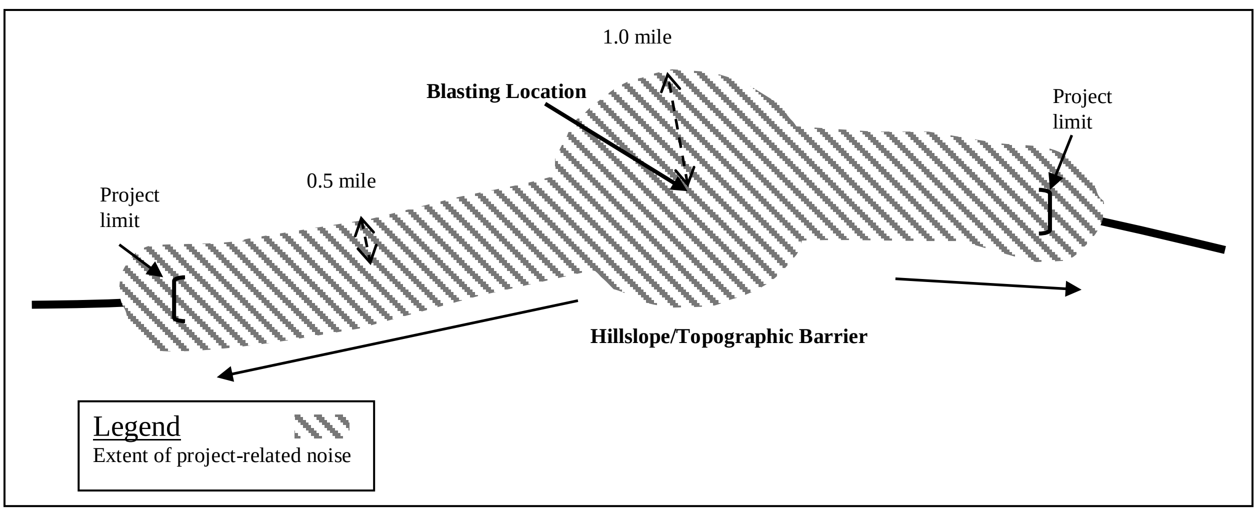

Figure 7-1. Extent of noise based on project activities and topography.

7.1.5 Species and Noise

So far, this discussion has focused on noise dynamics, generation, and prediction. The ability to identify and measure the extent of noise is only part of the assessment. The project biologist is also tasked with addressing the effects of noise on the species addressed in the BA.

7.1.5.1 How Animals Hear

Many animals hear sounds with frequencies above and/or below the range of human hearing. Some animals have ears that move and which are shaped to help localize the direction from which noise originates. Much is not known, but it is assumed that animals in general have better hearing than humans.

Not all animals respond the same way to similar sound sources, and not all individuals respond the same way within a species. Animal response to sound depends on a number of complicated factors, including noise level and frequency, distance and event duration, equipment type and condition, frequency of noisy events over time, slope, topography, weather conditions, previous exposure to similar noises, hearing sensitivity, reproductive status, time of day, behavior during the noise event, and the animal's location relative to the noise source (Delaney and Grubb 2003).

Different species exhibit different hearing ranges, so appropriate noise metrics and frequency ratings should be used when possible. For in-depth noise studies and hearing assessments, noise must be measured in a way that meaningfully correlates with the target species response. In this assessment, all decibel levels have been given as frequency weighted to approximate the way that humans hear. A-weighting (dBA) deemphasizes the upper and lower portions of the frequency spectrum, while emphasizing the middle portion of the spectrum (where humans have the greatest sensitivity). An audiogram (Figure 7-2) provides examples of the hearing range sensitivity for different species.

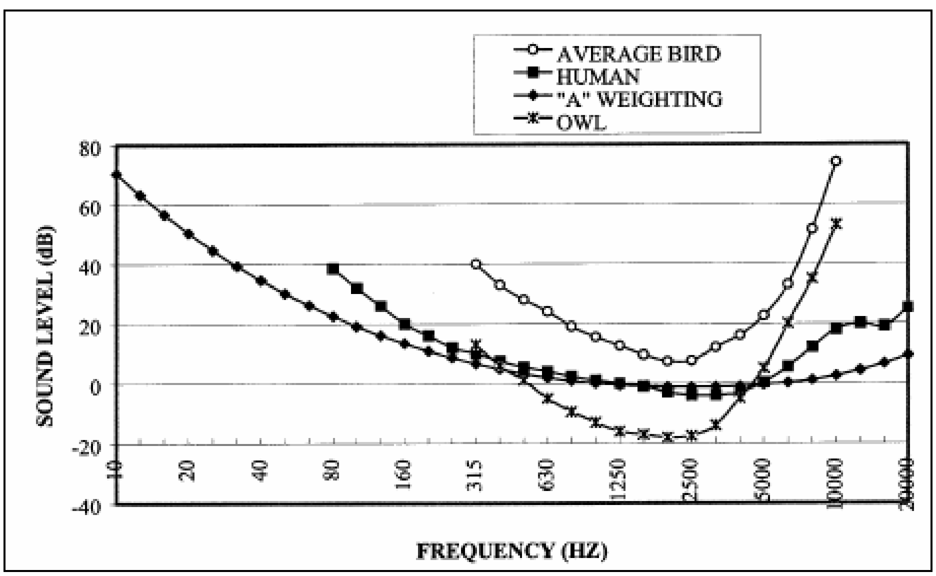

Figure 7-2. Example audiograms.

Source: Pater et al. (1999).

Notice how owls have better hearing than humans since they can detect noises in the same frequency range at lower decibel levels. An owl-weighted curve therefore emphasizes the middle frequency range where owls have the highest hearing sensitivity. The information presented in this discussion only uses A-weighted noise as a predictive factor. However, known threshold distances may provide the best available science source for understanding noise effects on species.

7.1.5.2 Threshold Distances and Effect Determinations

Threshold distances are defined as a known distance where noise at a given level elicits some response from a target species. This response can be visual, as in head-turning or flushing from a nest, or the animal may show little reaction.

In a previous biological opinion (BO) for the Olympic National Forest (USFWS 2003), the USFWS estimated the noise-only harassment/injury threshold for murrelets and owls was approximately 92 dBA at nest sites. The analysis determined noise levels at a distance by using a 7.5 dBA doubling distance reduction from noise-generating activities. This threshold is no longer being used in that manner.

In 2015, the USFWS published a BO for WSDOT activities (USFWS 2015). The BO establishes harassment/injury distances for noise-generating activities specific to marbled murrelets and northern spotted owls. It changes the thresholds from a noise-based measurement to a distance threshold. The distance-based threshold was established based on noise measurements.

It is important to note that the BO is only applicable for use in certain situations because it was developed for a specific program of activities. The thresholds and effect distances were determined after factoring a suite of activities and minimization measures specific to the project.

The 2015 statewide BO for the WSDOT programmatic uses standard threshold distances for several noise generating/disturbance activities to help determine potential effects to northern spotted owl (Table 7-11) and marbled murrelet (Table 7-12). The USFWS has replaced the 92 dBA threshold with the distance thresholds. The standard threshold distances described in the BO can be used as a tool to assist the biologist in typical transportation projects in making effect determinations for marbled murrelets and northern spotted owl.

Table 7-10. Disturbance, disruption (harass), and/or physical injury (harm) distance thresholds for northern spotted owl during the nesting season (March 1 to September 30). Distances are to a known occupied spotted owl nest tree or suitable nest trees in unsurveyed nesting habitat* (USFWS 2015).

Project Activity	**No Effect** (March 1 – Sept 30)	**NLAA** "may affect" disturbance distance (March 1 – Sep 30)	**LAA-Harass** Early nesting season disruption distance (March 1 – July 15)	**LAA-Harass** Late nesting season disruption distance (July 16 – Sep 30)	**LAA-Harm** Direct injury and/or mortality (March 1 – Sep 30)
Installing and Repairing Signs, Monitoring Devices, and Utilities	>0.25 mile	≤0.25 mile	NA	NA***	NA
Heavy Equipment Operation (including chainsaws	>0.25 mile	>195 feet to 0.25 mile	≤195 feet	NA***	NA
Pile-driving	>0.25 mile	360 feet to 0.25 mile	≤360 feet yards	NA***	≤15 feet (injury)
Blasting	>1 mile	0.25 to 1 mile	≤0.25 mile	NA***	≤300 feet (injury)
Short duration activities		Certain activities** that are within or adjacent to suitable spotted owl habitat may qualify for informal effects regardless of distance to activity from suitable habitat			

* This disturbance guidance applies to NRF habitat, disturbance to dispersal habitat is a NLTAA.

**The following activities may qualify for informal coverage under the WSDOT programmatic BA if they take less than 3 days from start to finish, and if approved by USFWS during Early Coordination

- Geotechnical investigations
- Sign/guardrail installation with no pile driving
- Vegetation maintenance, non-chainsaw, non-habitat removal
- Striping/delineation
- Oil distribution truck or trailer

***During the late nesting season, disturbance effects are considered discountable; therefore, they qualify for informal coverage.

Table 7-11. Disturbance, disruption (harass), and/or physical injury (harm) distance thresholds for marbled murrelet during the nesting season (April 1 to September 23). Distances are to a known occupied marbled murrelet nest tree or suitable nest trees in unsurveyed nesting habitat (USFWS 2015).

Project Activity	**No Effect**	**NLAA** “may affect” disturbance distance	**LAA-Harass** disruption distance	**LAA-Harm** Direct injury and/or mortality
Light maintenance (including road brushing and grading) at admin facilities, and heavily-used roads	>0.25 mile	≤0.25 mile	NA	NA
Chainsaws (includes felling hazard/danger trees)	>0.25 mile	328 feet to 0.25 mile	≤328 feet	Potential for mortality if trees felled contain platforms
Heavy equipment for road construction, road repairs, bridge construction, culvert replacements, etc.	>0.25 mile	328 feet to 0.25 mile	≤328 feet	NA
Pile-driving (steel H piles, pipe piles) Rock Crushing and Screening Equipment	>0.25 mile	363 feet to 0.25 mile	≤363 feet	≤15 feet (injury)
Blasting	>1 mile	0.25 to 1 mile	≤0.25 mile	≤300 feet (injury)
Short duration activities		Certain activities* that are within or adjacent to suitable murrelet habitat may qualify for informal effects regardless of distance to activity from suitable habitat		

*****The following activities may qualify for informal coverage under the WSDOT programmatic BA if they take less than 3 days from start to finish, use the murrelet timing restriction (no work until 2 hours after sunrise, and stop work 2 hours before sunset), and if approved by USFWS during Early Coordination

- Geotechnical investigations
- Sign/guardrail installation with no pile driving
- Vegetation maintenance, non-chainsaw, non-habitat removal
- Striping/delineation
- Oil distribution truck or trailer
- Projects conducted after September 4.

7.2 Underwater Noise

In-water work activities contribute to noise in the marine and freshwater environments. Underwater noise from pile driving activities is an issue of concern for both the Services. Past fish kills that resulted from in-water pile driving activities in Puget Sound, San Francisco Bay, and British Columbia, Canada, raised the Services' level of concern.

Noise behaves in much the same way in air as it does in water. The information and concepts presented here apply to both fresh and saltwater environments. Water currents bend noise waves upward when propagated into the current and downward downstream when observed over long distances. Noise waves bend towards colder denser water. Bottom topography and underwater structures can block, reflect, or diffract noise waves.

Underwater noise levels are measured with a hydrophone, or underwater microphone, which converts noise pressure to voltage, which is then converted back to pressure, expressed in Pascals (Pa), pounds per square inch (psi), or decibels (dB).[2] The current standard distance for measuring source noise levels is 10 meters from the source, where the source and receiver are within line of sight of each other (NMFS 2012a). Far field effects may result in calculations of a higher noise level at the receiver than would be measured in real time. Conversely, measurements taken too close to the source may result in near field effects, which may also result in inaccurate noise level calculations at the receiver. New standards are being developed for projects monitoring with more than one hydrophone. The most recent standards can be found in the underwater noise monitoring template found on the WSDOT website.

Noise levels measured in air are typically used to assess impacts on humans and thus decibels are weighted (dBA) to correspond to the way humans hear certain frequencies. Noise levels underwater are not weighted (dB) and thus measure all frequencies unmodified within the range of interest, which may extend below and above the audible range of many organisms.

Several descriptors are used to describe underwater noise. Two common descriptors are the instantaneous peak sound pressure level (dB_{peak}) and the Root Mean Square (dB_{RMS}) pressure level during the impulse, sometimes referred to as the peak and RMS level respectively. The peak pressure is the instantaneous maximum overpressure or underpressure observed during each pulse and can be presented in Pascals (Pa) or SPL in decibels (dB) referenced to a pressure of 1 micropascal (dB re: 1 µPa). The RMS level is the square root of the energy divided by the impulse duration. This level is the mean square pressure level of the pulse. It has been used by

[2]. Measurements are typically recorded electronically for analysis later. Pascals, or psi, can easily be converted to decibels (dB). To convert sound pressure energy to dB in air or water we use the same formula:

$$dB = 20 \log(p/pref)$$

Where dB is decibels, p is the pressure in micropascals (pascal multiplied by 10^6), pref is a reference pressure. When converting air pressure levels a reference pressure of 20 micropascals is used. The 20 micropascal reference for sound in human studies was selected because it is near the threshold of hearing at 1kHz for the average young person. When converting underwater pressure levels a somewhat arbitrary reference pressure of 1 micropascal is used. Thus in many reports in the literature, underwater decibels are reported as decibels re: 1 micropascal, indicating that the decibels are referenced to 1 micropascal. All underwater sound pressure levels given in this chapter are in decibels referenced to 1 micropascal (µPa).

NMFS to describe disturbance-related effects (harassment) to marine mammals from underwater impulse-type noises. When evaluating potential injury impacts to fish, peak sound pressure (dB_{peak}) is often used.

It is not possible to convert peak levels to RMS levels directly, but a conservative rule of thumb can be applied in noise assessments. Peak levels are generally 10 to 20 dB higher than RMS levels. To convert from peak to RMS, subtract 10 dB. This likely overestimates the RMS value, but enables the assessment to remain as conservative as possible. Likewise, to convert from RMS to peak, add 20 dB. This again may overestimate the actual peak noise level, but will provide a conservative estimate.

Sound Exposure Level (SEL) is often used as a metric for acoustic events and is often used as an indication of the energy dose. SEL is calculated by summing the cumulative pressure squared (p^2), integrating over time, and normalizing to 1 second. This metric accounts for both negative and positive pressures because p^2 is positive for both, and both are treated equally in the cumulative sum of p^2 (Hastings and Popper, 2005). The units for SEL are dB re: 1 μPa^2 sec.

7.2.1 Noise Generation, Transmission, and Reduction

Transmission loss (TL) underwater is the accumulated decrease in acoustic intensity as an acoustic pressure wave propagates outwards from a source. The intensity of the source is reduced with increasing distance due to spreading. Spreading can be categorized into two models, spherical spreading and cylindrical spreading models.

7.2.1.1 Transmission Loss Calculations for Underwater Noise Levels

Spherical (free-field) spreading occurs when the source is free to expand with no refraction or reflection from boundaries (the sediment or water surface). The TL for spherical spreading is defined by the formula:

$$\mathbf{TL = 20 \log(R)}$$

R is the range or distance from the source. Spherical spreading results in a general 6 dB decrease in the intensity of the noise per doubling of distance.

Cylindrical spreading applies when noise energy spreads outwards in a cylindrical fashion bounded by the sediment and water surface. Cylindrical spreading is defined by the formula:

$$\mathbf{TL = 10 \log(R)}$$

This results generally in 3 dB per doubling of distance transmission loss of underwater noise. However, many construction projects produce noise in shallow water, and reflections from the sediment or water surface can reduce spreading considerably. Because of the complexity of these reflections it is difficult to define TL. Since noise energy is not perfectly contained by reflection and refraction, most experts agree that the true spreading is often somewhere between 3 and 6 dB per doubling of distance, or approximately 4.5 dB per doubling of distance (Vagle 2003).

Currently, the Services use the practical spreading loss calculation (NMFS 2012a), where:

$$\mathbf{TL = 15Log(R_1/R_2)}$$

Where:

- R1 is the range or distance at which transmission loss is estimated.
- R2 is the range or distance of the known or measured sound level

Conversely the distance to where the source sound level drops off to some pre-determined sound level (the background sound level) can be calculated by rearranging the terms in the equation above giving:

$$\mathbf{R_1 = R_2 * 10^{(TL/15)}}$$

Where:

- TL = the difference between the source sound level and the background or other sound level at some distance.

This calculation assumes that noise energy decreases at a rate of 4.5 dB per doubling of distance, which is in between the spherical (6 dB) and cylindrical (3 dB) calculation. The complete equation for transmission loss includes a linear term in addition to the geometric term. A complete transmission loss equation might look like:

$$\mathbf{TL = 15\log(R_1/R_2) + \alpha R}$$

Where:

- αR is the linear absorption and scattering loss.

The linear term will have a greater influence on transmission loss 1,000 meters beyond the source. There is not common agreement on what should be used for the alpha term in the equation above, particularly for shallow water environments. Therefore, the linear term should be ignored for the present time until a decision can be made on the appropriate value to be used for alpha.

Dahl et al. (2012) state that the underlying characteristic of transmission loss for pile driving in marine environments is cylindrical spreading; however, like propagation in air, a number of other factors, such as temperature gradients and currents, modify this characteristic. The common occurrence of decreasing temperature with depth can create significant shadow zones (noise refracts or bends towards the colder deeper water as it does in air) where the SPL can be as much as 30 dB lower than that from cylindrical spreading. In shallow water (less than 200 meters depth), reflections from the surface and bottom combine in such a way that the sound field becomes homogenous throughout the water column at distance of approximately 3H where H is the water depth at the pile (Dahl et al., 2012). Thus, underwater noise propagation is highly variable. Monitoring data from some pile driving projects indicate that the actual spreading loss is intermediate between cylindrical and spherical spreading (Reyff et al., 2003; Thomsen et al. 2006) while other data indicates that the actual spreading loss is closer to spherical spreading (Laughlin 2010a, 2010b). Therefore, until a better spreading model can be developed and agreed on, a practical spreading model, as described by Thomsen et al. (2006) is most appropriate.

7.2.1.2 Noise Reduction Factors

Hydrographic Conditions that Affect Noise Transmission

In a current or strong tidal flux, noise propagated into the current would be refracted toward the surface where it would be quickly attenuated. However, this would depend on the velocity of the current and would occur on a scale of several hundred feet or more. This has not been researched adequately to make definitive determinations.

The water depth in which frequencies propagate must be greater than one-quarter the wavelength or $h = \lambda/4$ where h = water depth and λ = wavelength (Urick 1983). Wavelength is determined by $\lambda = c/f$ where f = frequency in Hz and c = speed of noise in water (approximately 5,000 feet/sec). Since the dominant frequencies generated in pile driving are between 50 and 1,000 Hz, most of the energy is not propagated in water depths of 0.4 meters (1.3 feet) or less. However, some noise propagates through the sediment, especially the harder sediments, such as clay and rock, escaping into the water column at a distance dependent upon the mach angle, albeit at a lower level than the source (Reinhall and Dahl, 2011).

Bottom Topography

The method of determining how noise attenuates as it moves away from the source can be difficult and site specific. It is dependent on sediment types, bottom topography, structures in the water, slope of bottom, temperature gradients, currents, and wave height. In the Puget Sound region, generally the sediments are relatively soft and the bottom slopes away from the shore relatively quickly. Depending on location and season, there can also be a relatively strong tidal flux in Puget Sound.

River Sinuosity

Noise propagation in rivers is limited by the sinuosity of a system. For example, where a river bends, noise is unlikely to propagate. A line-of-sight rule, meaning that noise may propagate into any area that is within line-of-sight of the noise source, is used to determine the extent of noise propagation in river systems.

7.2.2 Baseline Underwater Sound Conditions

Existing underwater sound levels can serve as a baseline from which to measure potential disturbance impacts associated with project activities. Both ambient or natural noise sources and mechanical or human generated background sound contribute to the baseline sound conditions of a project site.

7.2.2.1 Ambient or Background Sound Levels

There are numerous contributing sources to background marine sound conditions. Sound levels produced by natural sources include snapping shrimp (71 dB) (Urick 1983), lightning strikes (260 dB), waves breaking, and rain on the ocean surface. Sound levels produced by human or mechanical sources include large tankers and naval ship engines (up to 198 dB) and 180+ dB for depth sounders (Buck 1995; Heathershaw et al. 2001). Commercial sonar devices operate in a frequency range of 15 kHz to 200 kHz and in an acoustical range of 150 to 215 dB (Stocker 2002). These levels are maximum source levels.

Underwater background broadband sound levels measured at several ferry terminals in Puget Sound ranged from 107 to 122 dB_{RMS} (Laughlin 2019b). In a study conducted in Haro Strait, San Juan Islands, data showed that the broadband background half-hourly SPL in Haro Strait ranged from 95 dB to 130 dB (Veirs and Veirs 2006). Broadband measurements are those which cover the entire applicable frequency range for the instrument. This same study indicated that 2-second SPL averages are lowest in the winter, slightly higher during summer nights, and highest during summer days as a result of small boat traffic.

WSDOT analyzed broadband background sound (20 Hz to 20 kHz) over three consecutive 24-hour periods at Mukilteo, Port Townsend, Anacortes, Edmonds, and Seattle. The decibels reported for these locations represent 50 percent of the cumulative distribution functions (CDF) of these three periods for daytime sound levels. The CDF is the function that maps values to their percentile rank in a distribution, which in this case is a log-normal distribution. The normal distribution shows the probability that a certain value will fall within a certain range and the CDF maps that distribution. The 50^{th} percentile of the CDF is reported for underwater background sound levels as a measure of central tendency. Based on WSDOT's recent research, the broadband sound level varies by ferry terminal location and time of day (Tables 7-13 and 7-14). Also note that background sound at these locations is also available for each of the hearing frequency groups of marine mammals (Tables 7-13 and 7-14). For projects occurring in the vicinity of any of these locations, these background sound levels should be assumed. Broadband background data will only be used for projects which are not conducting marine mammal ESA or MMPA consultations or for projects conducting marine mammal ESA and MMPA consultations where background data is not available by frequencies which match the marine mammal functional hearing groups. Background sound levels in deep freshwater lakes or deep slow moving rivers are approximately 120 dB_{RMS}, similar to marine levels near developed shorelines. In shallow (1 foot deep or less), fast moving rivers, the ambient sound levels are louder due to the water moving over rocks and boulders and the wave action at the surface. Background levels are estimated at 140 dB_{RMS} in these systems (WSDOT 2004).

For areas where site-specific sound data is not available, NOAA has developed guidance for collecting background sound data for use in marine mammal consultations and permit applications. This guidance is available on the web at: < http://www.westcoast.fisheries.noaa.gov/publications/protected_species/marine_mammals/killer_whales/esa_status/characterize_background_sound_guidance_memo.pdf >. For ferry projects that cannot collect new background sound data, a rough estimate for background sound can be generated as follows: 1) calculate the number of ferry vessels per day at the project site; 2) find one of the sites listed above or in Tables 7-13 and 7-14 below that has a similar level of vessel traffic; 3) use the background sound levels at the chosen site above or in Table 7-13 or 7-14 as an approximation of background sound levels at the project site.

Table 7-12. 72-hour Continuous Underwater Background Noise Levels

Ferry Terminal	Functional Hearing Groups					
	1 Hz to 20 kHz	7 Hz to 20 kHz	50 Hz to 20 kHz	60 Hz to 20 kHz	150 Hz to 20 kHz	275 Hz to 20 kHz
	Broadband Background (fish and murrelet) (dB)	Low Frequency Cetaceans (dB)	Phocid Pinnipeds (dB)	Otariid Pinnipeds (dB)	Mid-frequency Cetaceans (dB)	High-frequency Cetaceans (dB)
Port Townsend[1]	108	107	105	105	100	99
Anacortes[2]	121	116	112	112	106	104
Edmonds[2]	116	114	110	110	104	102
Seattle[2]	119	117	113	113	107	106
Mukilteo (2011)[2]	117	115	111	111	105	103
Mukilteo (2015)[2]	117	112	110	110	104	102
Kingston[2]	118	116	109	109	101	98
Vashon[2]	119	116	111	111	105	103
Southworth[2]	117	114	110	110	105	103
Coupeville[2]	118	113	109	109	104	102
Lake Keechelus[3]	107	-	-	-	-	

[1] Dahl et al. 2010.
[2] Laughlin, 2019b.
[3] Soderberg and Laughlin 2016b.

Table 7-13 Underwater Background Noise Levels for Daytime Only.

Ferry Terminal	Functional Hearing Groups					
	1 Hz to 20 kHz	7 Hz to 20 kHz	50 Hz to 20 kHz	60 Hz to 20 kHz	150 Hz to 20 kHz	275 Hz to 20 kHz
	Broadband Background (fish and murrelet) (dB)	Low-frequency Cetaceans (dB)	Phocid Pinnipeds (dB)	Otariid Pinnipeds (dB)	Mid-frequency Cetaceans (dB)	High-frequency Cetaceans (dB)
Port Townsend[1]	108	107	105	105	100	99
Anacortes[2]	122	118	113	113	107	105
Edmonds[2]	117	115	112	111	106	104
Seattle[2]	120	118	114	114	109	107
Mukilteo (2011)[2]	118	116	112	112	106	105
Mukilteo (2015)[2]	118	116	111	111	105	103
Kingston[2]	118	116	109	110	101	98
Vashon[2]	120	117	113	113	107	106
Southworth[2]	117	115	111	111	106	104
Coupeville[2]	118	114	110	110	104	102
Lake Keechelus[3]	107	-	-	-	-	

[1] Dahl et al. 2010.
[2] Laughlin, 2019b.
[3] Soderberg and Laughlin 2016b.

Other considerations for determining background sound at a project site are whether or not pile driving will occur during the day or at night and what season the project will be constructed. Background data collected in Puget Sound show differences between day and night and between summer and winter levels. The difference between summer and winter underwater background sound in many parts of Puget Sound differs by 3 dB – it is 3 dB noisier in the summer due to recreational boat traffic. It is also noisier in the day time than night time. Background data should be collected for the same time of year during which the pile driving project will occur.

However, if a project only has fall, winter or spring monitoring data, but is pile driving in the summer, 3 dB can be added to the background sound level. In addition, since pile driving normally occurs during the daytime, use the numbers reported for daytime background sound.

7.2.3 Underwater Construction Noise

Although there are many sources of noise in the underwater environment, the most common sources of noise associated with construction activities are impact and vibratory hammers. Underwater noise from pile driving is generated using different types and diameters of piles, types of hammers, and by driving the piles into different types of substrates. Each configuration can produce different noise levels and waveform characteristics.

Noise generated by impact pile driving is impulsive in nature. Impulsive noises have short duration and consist of a broad range of frequencies. Impulsive waveforms are characterized by a rapid pressure rise time (the time in milliseconds it takes the wave form to rise from 10 percent to 90 percent of its highest peak) that occurs within the first few milliseconds followed by rapid fluctuation (underpressure and overpressure) about the ambient pressure.[3] Although other methods such as peak-to-peak or zero-to-peak are used by some researchers to define rise time the method of calculating rise time noted above has become the standard for pile driving waveforms. Although there is no definitive correlation between rise time and injury to fish it is thought that a rapid rise time may cause injury.

This section provides general information regarding potential sound levels and characteristics associated with various equipment and pile types. NOAA has developed guidance for more accurately characterizing and collecting source sound data from impact and vibratory pile driving, for use in marine mammal consultations and permit applications. This guidance is available on the web at:
http://www.westcoast.fisheries.noaa.gov/publications/protected_species/marine_mammals/killer_whales/esa_status/characterize_pile_driving_source_levels_guidance_memo.pdf

7.2.3.1 Pile Installation Equipment

There are five pile-driving hammer types that are commonly used. Vibratory hammer, diesel hammer, air or steam hammer, hydraulic hammer, and drop hammer used for smaller timber piles. Wave forms generated by each of these hammer types are described below.

Vibratory hammers vibrate the pile into the sediment by use of an oscillating hammer placed on top of the pile. The vibratory action causes the sediment immediately surrounding the pile to liquefy and the pile can be driven through the sediment. In some cases, piles can be driven by vibratory hammers to a depth where they can reach load bearing capacity, but the bearing

[3] The total duration of the impulse varies based on several factors, which include the force applied to the pile, the nature of the pile (wood, concrete, or steel as well as diameter) and the substrate into which the pile is being driven. In general, most of the energy associated with each impulse occurs within the first 30 to 50 milliseconds. Recent measurements of underwater sound generated by impact pile driving have shown that most of the energy is contained in a frequency range between approximately 25Hz and 1.6 kHz. Within this frequency band the highest energy densities are found between 50 and 350 Hz (Reyff et al. 2002).

capacity must be tested with the use of an impact hammer. This is referred to as proofing. To proof a pile, it is struck with an impact hammer until the bearing capacity can be measured. This may take just a few strikes or several strikes depending on site-specific characteristics.

Peak noise levels can exceed 206 dB; however, the rise time is relatively slow (Figure 7-3). Vibratory driving noise levels are generally 10 to 20 dB lower than impact hammer driving. Vibratory installation of steel piles in a river in California resulted in sound pressure levels that were not measurable above the background noise created by the current (Reyff 2006).

Impacts on fishes or other aquatic organisms have not been observed in association with vibratory hammers. This may be due to the slower rise time and the fact that the energy produced is spread out over the time it takes to drive the pile. As such, vibratory pile driving is generally considered less harmful to aquatic organisms and is the preferred method.

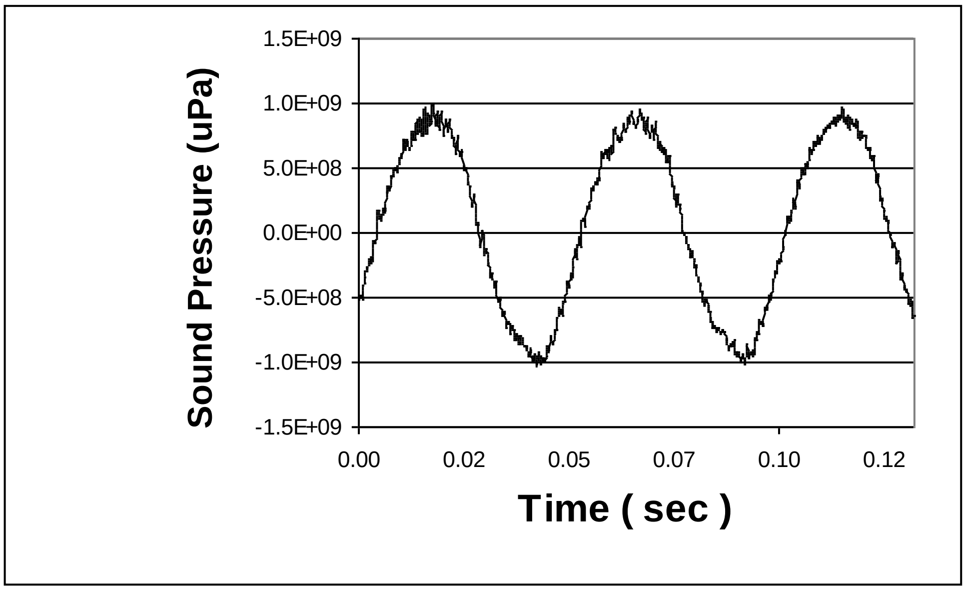

Figure 7-3. Typical vibratory hammer wave form.

Air or steam-driven impact hammers use air to lift a heavy piston and then use gravity to drop the piston onto the top of the pile. The height of the piston can be varied to allow more potential energy to transfer to the piston and then transfer as kinetic energy into the pile. Air hammers produce underwater noise waveforms with each pile strike that are similar to diesel hammers (Figure 7-4). Therefore, noise levels and rise time are similar for air hammers and diesel hammers.

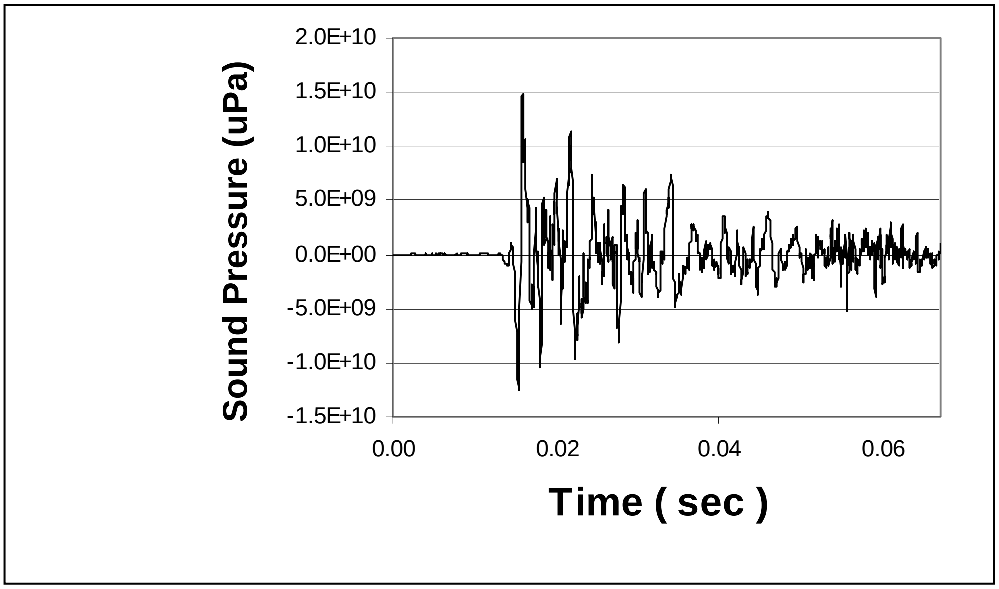

Figure 7-4. Typical air hammer wave form for a single pile strike.

Diesel-driven impact hammers ignite diesel fuel to lift a heavy piston and then use gravity to drop the piston onto the top of the pile. The height of the piston can be varied somewhat by varying the amount of diesel fuel going into the combustion chamber. Diesel hammers produce underwater noise waveforms with each pile strike that are similar to air hammers (Figure 7-5).

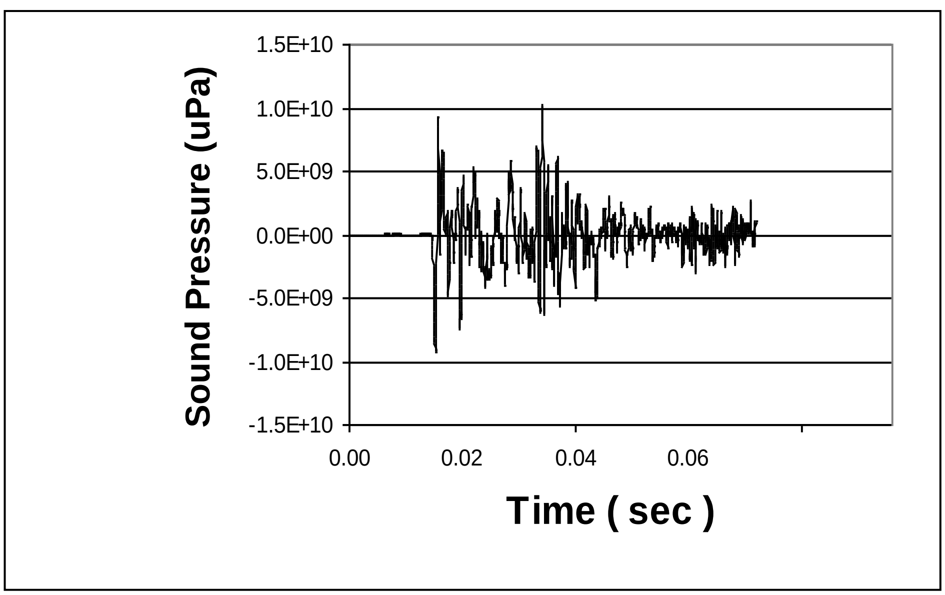

Figure 7-5. Typical diesel hammer wave form for a single pile strike.

Hydraulic driven impact hammers use hydraulics to lift a heavy piston and then use gravity to drop the piston onto the top of the pile. In addition, with some hydraulic hammers, hydraulic pressure is used to drive the hammer into the pile instead of using gravity. Hydraulic hammers produce a somewhat different waveform signature with a much more rapid rise time (Figure 7-6). The diesel hammer is the recommended hammer to use based on rise time data gathered from the Friday Harbor Ferry Terminal Study.

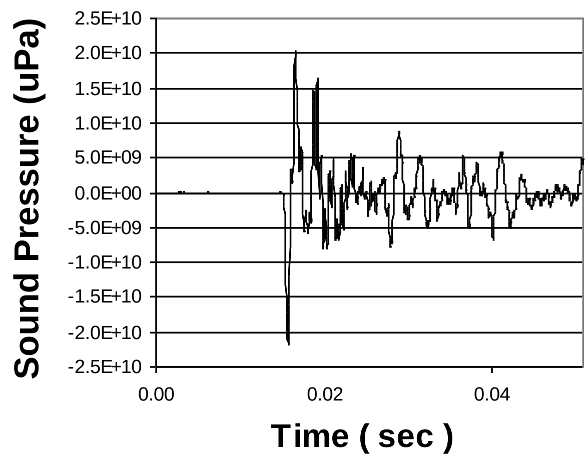

Figure 7-6. Typical hydraulic hammer wave form for a single pile strike.

7.2.3.2 Different Pile Types

The size and type of pile also affect the sound generated by pile-driving activities. There are several types of piles typically used in transportation projects, including timber, concrete, and steel. Piles can vary considerably in diameter, or be in the form of H piles and sheet piles. Sound pressure levels associated with each of these types of piles are summarized in Tables 7-15 and 7-16. Sound levels from projects within Washington State are used when available for calculating effects in biological assessments. If the biologist does not have site-specific information, a comparison with other projects with the same pile type and size, and similar substrates is appropriate in estimating source noise levels. The sound levels are denoted as either peak, RMS, or SEL; and all are attenuated values and measured at 10 meters from the pile unless otherwise noted.

Other considerations include:

- Peak levels are generally 10 to 20 dB higher than RMS levels.
- Peak pressures occur between 1 millisecond (msec) very close to the pile and 5 to 6 msec after the strike at a distance of 20 meters from the pile.
- The greater the pile surface exposed under the water, the more acoustic energy radiates. Shallower water (less than 2 feet deep) does not propagate noise energy effectively, especially at lower frequencies (Urick 1983).

Table 7-14. Attenuated sound pressure levels associated with pile types during impact pile driving.

Location	Pile Diameter (in)	Measurement Distance (m)	Water Depth (ft)	Hammer Type	Total Number of Strikes	Peak (dB)	$RMS_{90\%}$ (dB)	Single Strike $SEL_{90\%}$ (dB)	Cumulative SEL (dB)
Steel Pipe									
Cape Disappointment Boat Launch[1]	12	10	26	Air	191	198	181	166	189
SR 240 Bridge[2]	16	9	17	ICE 605 Diesel	>183	200	187	173	196
SR 202 Evans Creek Bridge[3]	16	9	2	Diesel	35	179	174	164	179
Wahkiakum Ferry Terminal[4]	18	11-13	10	DelMag D30-32 Diesel	757	195	169	166	195
Bainbridge Terminal[5]	24	10	11	Diesel	207	206	195	179	202
Coupeville Terminal[6]	24	12	15	Diesel	354	206	193	178	200
SR 411 Lexington Bridge[7]	24	10	3	ICE 60S Diesel	12	202	168	-	-
SR 24 Bridge[8]	24	10	0.5	ICE 60S Diesel	99	199	182	164	184
Friday Harbor Terminal[9]	24	10	33	Diesel	130	210	189	182	203
	24	10	44	Air	477	202	181	174	201
	24	10	33	Hydraulic	378	205	186	178	204
	30	10	34	Diesel	114	207	191	182	203
Port Townsend Terminal[10]	24	10	20	Diesel	141	200	185	171	191
	30	10	20	Diesel	259	197	182	170	192
SR 520 Bridge	24[11]	10	28	Impact	123	204	189	174	195
	30[12]	10	10	-	92	209	191	179	197
Vashon Ferry Terminal[13]	30	16	74	DelMag D62 Diesel	47	215	195	186	203
I-90, Yakima River[14]	30	10	3	Diesel	224	195	180	170	198
Eagle Harbor Maintenance[15]	30	10	33	DelMag D62 Diesel	29	194	184	182	197
Colman Dock Test Pile[16]	24	15	12	Diesel	64	180	165	155	173
	36	14	6		529	205	189	176	193
Colman Dock Phase 2[24]	24	11	38	Ice I-100V2 Diesel	126	194	176	166	185
	36	18	47		54	205	191	178	193
Mukilteo Terminal[17, 25]	36	10	24	DelMag D62 Diesel	73	203	189	175	206
	30	10	30	Diesel	205	193	185	170	193
Anacortes Terminal[18]	36	10	42	Diesel	323	207	189	175	211
Humboldt Bay, California[19]	60	10	15	Diesel	-	207	192	-	-
Richmond-San Rafael Bridge[19]	66	10	13	DelMag D62 or D100	-	210	195	-	-
SR 529 Ebey Slough Bridge[20]	72	10	7	Diesel	26	214	189	182	196
Benecia-Martinez Bridge[19]	96	10	6	Hydraulic Menck MHU500T	-	220	205	194	-
Richmond-San Rafael Bridge[19]	126	11	>49	Hydraulic Submersible IHC	-	213	202	-	-
Thorsen and Reyff 2003[21]	150	100	-	-	-	200	185	-	-
Steel H-pile									
SR 202 Evans Creek[3] (upland)	12	10	0.5	Diesel	82	173	157	147	166
I-5 Puyallup River Bridge[22]	14	10	4	Diesel	577	191	174	160	184
Concrete									
Berkeley Marina, California[19]	18 (octagonal)	10	<12	ICE-60	-	185	166	155	-

Location	Pile Diameter (in)	Measurement Distance (m)	Water Depth (ft)	Hammer Type	Total Number of Strikes	Peak (dB)	$RMS_{90\%}$ (dB)	Single Strike $SEL_{90\%}$ (dB)	Cumulative SEL (dB)
Mukilteo Terminal[17]	24 (octagonal)	10	25	DelMag D62 Diesel	184	184	170	159	210
	36 (hollow)	10	28	DelMag D62 Diesel	204	193	183	167	210
Colman Dock Test Pile[16]	36 (hollow w/stinger)	10	10	Diesel	193	197	184	172	192
	18 (octagonal w/stinger)	10	10	Diesel	835	190	175	164	191
Timber									
Ballena Bay Marina, California[19]	12	10	12	3,000 lb. Drop	-	180	170	160	-
Steel Sheet									
Port of Oakland, California[19]	24	10	49	Diesel	-	205	190	180	-
Double-walled/Mandrel									
Commencement Bay[12]	30	10	24	DelMag D46	-	190	179	-	182
Vashon (test pile)[23]	30	20	22	DelMag D46	402	199	186	172	191

[1] Laughlin, 2006a.
[2] Laughlin, 2004.
[3] Laughlin, 2006b.
[4] Laughlin, 2010c.
[5] Laughlin, 2005.
[6] Ghebreghzabiher, 2017.
[7] Magnoni, 2006.
[8] Laughlin, 2005c.
[9] Laughlin, 2005b.
[10] Magnoni et al. 2014.
[11] Ghebreghzabiher, 2014.
[12] Soderberg, 2016a.
[13] Laughlin, 2010a.
[14] Laughlin, 2019c.
[15] Jasco, 2005.
[16] Soderberg and Laughlin, 2016a.
[17] Laughlin, 2007.
[18] Sexton, 2007.
[19] CalTrans, 2015.
[20] Laughlin, 2011a.
[21] Thorson and Reyff, 2003.
[22] Laughlin, 2016.
[23] Soderberg, 2016b.
[24] Greenbusch Group, Inc. 2019
[25] Laughlin, 2018b

Table 7-15. Broadband sound pressure levels associated with pile types during vibratory pile driving/removal.

Location	Pile Diameter (in)	Measurement Distance (m)	Water Depth (ft)	Hammer Type	Duration (minutes)	RMS (dB)	Cumulative SEL (dB)
Steel Pipe							
Sausalito Dock, California[1]	12	10	<16	3,000 lb. Drop	-	155	155
Friday Harbor Terminal[2]	24	10	17	APE	-	162	-
Manette Bridge[3]	24	10	12	APE	-	166	-
Coupeville (Keystone) Terminal[4]	30	6	30	APE	-	176	-
Colman Dock Terminal (battered pile)[5]	30	10	74	APE Super Kong	-	169	222
Vashon Ferry Terminal[6]	30	16	40	APE	-	169	-
Port Townsend Terminal (test pile)[7]	30	10	29	APE Super Kong 600	-	166	-
	36	10	31	APE Super Kong 600	-	165	-
Edmonds Terminal[8]	30	10	42	J&M 66	-	166	-
	36	11	38	J&M 66	-	163	-
Anacortes Terminal[9]	36	10	74	APE King Kong	63	170	228
Edmonds Terminal (reset)[10]	36	10	32	APE	-	150	184
Kingston Terminal (reset)[10]	36	10	28	APE	-	184	216
Richmond Inner Harbor, California[1]	72	10	<16	APE Super Kong	-	180	180
Steel H-pile							
Bainbridge Terminal[11]	12	10	34	APE	27	153	191
Fauntleroy Terminal[11]	12	10	24	APE	3.2	137	160
Steel Sheet							
Port of Oakland, California[1]	24	10	49	APE	-	165	165
Plastic and Steel							
Anacortes Terminal[9]	13	10	52	IOF 416	1.3	152	178
Timber							
Port Townsend Terminal[12]	12	10	35	ICE 416	-	150	-

Location	Pile Diameter (in)	Measurement Distance (m)	Water Depth (ft)	Hammer Type	Duration (minutes)	RMS (dB)	Cumulative SEL (dB)
Ballena Bay Marina, California[1]	14	10	-	-	-	161	-

[1] CalTrans 2015
[2] Laughlin, 2010d.
[3] Laughlin, 2010f.
[4] Laughlin, 2010e.
[5] Laughlin 2012b.
[6] Laughlin 2010b.
[7] WSDOT 2010.
[8] Laughlin 2011b.
[9] Laughlin 2012a.
[10] Laughlin 2017b.
[11] Laughlin 2019a.
[12] Laughlin 2011c.

Tables 7-17, 7-18, 7-19, and 7-20 provide underwater sound pressure levels associated with other activities, including hoe-ram operation, terrestrial blasting, and geotechnical investigations.

Table 7-16. Sound pressure levels associated with hoe-ram operation (broadband).

Location	Measurement Distance (m)	Water Depth (ft)	Total Number of Strikes	Hoe-Ram Energy Rating (ft-lbs.)	Peak (dB)	$RMS_{90\%}$ (dB)	$SEL_{90\%}$ (dB)	cSEL (dB)
Concrete Pier								
SR 303 Manette Bridge[1]	10	17	707	9,293	205	186	171	196
SR 520 Concrete Pier[2]	10-15	14	1,750	--	193	174	163	171

[1]Escude 2012.
[2]Escude 2017.

Table 7-17. Underwater sound pressure levels associated with upland blasting (broadband).

Location	Measurement Distance (m)	Water Depth (ft)	Charge Weight (lbs)	Peak (dB)	$RMS_{90\%}$ (dB)	$SEL_{90\%}$ (dB)	cSEL (dB)
Upland Blast							
I-90, Keechelus Lake[1, 2]	257	226	30	170	159	152	157
	38	6	24	181	172	164	163

[1] Laughlin, 2017c.
[2] Laughlin, 2018.

Table 7-18. Sound pressure levels associated with underwater geotechnical investigations (broadband).

Location	Measurement Distance (m)	Water Depth (ft)	Activity	# Strikes	Peak (dB)	$RMS_{90\%}$ (dB)	$SEL_{90\%}$ (dB)	cSEL (dB)
Mukilteo Ferry Terminal[1]	10	45	Hammering	49	181	158	148	165
			Drilling	-	152	143	-	-

[1] Gilbertson, 2007.

Table 7-19. Sound pressure levels associated with underwater chainsaw (broadband).

Location	Measurement Distance (m)	Water Depth (ft)	Activity	# Strikes	Peak (dB)	$RMS_{90\%}$ (dB)	$SEL_{90\%}$ (dB)	cSEL (dB)
Colman Dock Phase 2 [1]	10	30	Chain sawing	N/A	159	140	140	152

[1] Greenbusch Group, Inc. 2019

The use of an underwater sound level meter can provide real-time sound pressure levels. This information can be used to adjust the area of marine mammal monitoring if different from estimated disturbance zone distances. In some cases, reductions in the sizes of monitoring zones can be significant. Table 7-21 summarizes the measured distances to the disturbance boundary based on the use of a sound level meter.

Table 7-20. Sound pressure levels measured with an underwater sound level meter during vibratory pile driving.

Ferry Terminal	Pile Diameter (inches)	Measured Distance to ZOI Boundary (miles)	Functional Hearing Groups					
			1 Hz to 20 kHz	7 Hz to 20 kHz	50 Hz to 20 kHz	60 Hz to 20 kHz	150 Hz to 20 kHz	275 Hz to 20 kHz
			Broadband Background (fish and murrelet) (dB)	Low-frequency Cetaceans (dB)	Phocid Pinnipeds (dB)	Otariid Pinnipeds (dB)	Mid-frequency Cetaceans (dB)	High-frequency Cetaceans (dB)
Orcas Island (timber)* [1]	12	1.6	131	131	128	128	127	126
Orcas Island (steel)** [1]	24	6.2	130	130	129	129	129	129
Mukilteo[2]	30	4.9	120	-	-	-	-	-
Colman[3]	24	3.0	137	137	136	136	135	135
	36	4.3	134	134	132	132	132	132
Bainbridge (H pile)[4]	12	4.9	145	120	100	98	111	111

* Measured at 572 meters (0.4 mile)
** Measured at 2040 meters (1.3 miles)
[1]Laughlin 2013.
[2]Laughlin 2017b.
[3]Soderberg 2016.
[4]Laughlin 2019a.

7.2.3.3 Noise Reduction Strategies

Various measures have been developed to reduce underwater noise generated by pile driving. These include air bubble curtains (confined or unconfined), temporary noise attenuation piles, air filled fabric barriers, and isolated piles or cofferdams. An air bubble curtain is a device used during pile driving that infuses the area surrounding piles with air, thereby generating a bubble screen. The purpose is to reduce peak underwater sound pressure levels (SPLs), thereby reducing potential adverse effects to aquatic organisms.

The components of a bubble curtain typically include a high volume air compressor, primary and secondary feed lines, and air distribution manifolds. Longmuir and Lively (2001) recommended that manifolds should have 1/16-inch air release holes every 3/4-inch along their entire length (Figure 7-7). The Services currently recommend basing bubble curtain design on that described in

Longmuir and Lively (2001). The air distribution manifolds are placed surrounding the piling below the water surface where the pile meets the sediment. An effective bubble curtain system should distribute air bubbles that completely surround the perimeter of a pile to the full depth of the water column. Maintaining the optimal size of the bubbles, based on their resonant frequency, greatly enhances the noise attenuation of the bubble curtain (Vagle 2003).

In areas where currents exist, where the seafloor or substrate is not level, or piles are being driven at an angle other than 90 degrees to the water surface, the size or number of manifolds should increase to provide coverage throughout the water column. In some of these cases, particularly where currents can move the curtain away from the pile, unconfined bubble curtains may prove ineffective, and a confined system may be required.

Bubble curtains are not used when piles are driven in water that is less than two feet deep. Underwater noise propagation is generally poor in shallow conditions.

Proper design and implementation are key factors in bubble curtain effectiveness for reducing SPL. Studies on the effectiveness of bubble curtains for reducing noise pressure waves have found varied results. MacGillivray et al. (2007) and Reyff et al (2003) reviewed previous reports, and also conducted a study on the use of bubble curtains and their reduction of noise pressure waves. In previous studies, Reyff et al (2003) found that bubble curtains resulted in a 0 to 10 dB reduction in RMS. While monitoring pile driving of three large piles (inside diameter of 8 feet, outside diameter of 8.5 feet), bubble curtains reduced peak pressures from 6 to over 20 dB and RMS values from 3 to 10 dB. Thorson and Reyff (2003) found similar results with a reduction of from 5 to 20 dB in peak SPLs. Vagle (2003) studied the underwater effects of pile driving at four locations in Canada. This study reported reductions of between 18 dB and 30 dB.

Reyff et al. (2002) evaluated the effectiveness of an isolated pile (IP) technique using a confined bubble curtain system. The IP was 3.8 meters in diameter with the interior coated with 2.54 centimeter closed cell foam. In this type of bubble curtain system, the IP surrounds the actual driven pile, and contains the bubble flow. The IP and bubble curtain system provided a dramatic reduction in both peak pressures and RMS levels. Peak pressures were reduced by 23 to 24 dB and RMS levels were reduced by 22 to 28 dB. Most of the reduction in noise energy occurred at frequencies above 100 Hz.

WSDOT conducted a test pile project for the Vashon Ferry Terminal (Laughlin, 2010a) where the University of Washington Applied Physics Lab and Department of Mechanical Engineering tested a Temporary Noise Attenuation Pile (TNAP) which consisted of an inner and outer steel casing with an inner air chamber between the casings that was partially filled with foam. At the bottom on the inside of the inner casing was a bubble ring. Sound reduction achieved ranged between 8 and 14 dB with an overall average of 11 dB. Most of the reduction in noise energy occurred at frequencies above approximately 800 Hz.

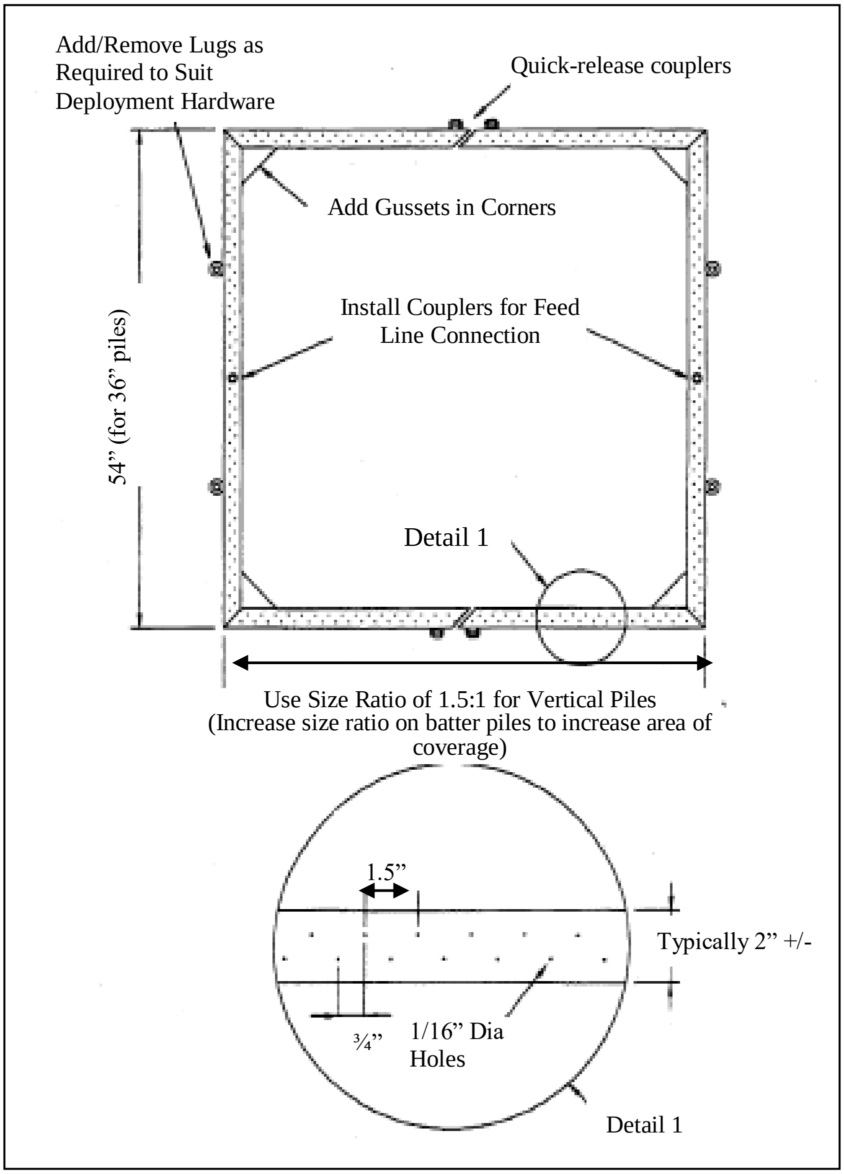

Figure 7-7. Air manifold design.
Source: Longmuir and Lively (2001).

In 2015, the University of Washington and WSDOT conducted another test pile project at the Vashon Ferry Terminal. The test piles consisted of a double wall pile and a mandrel-driven pile. The double wall pile consists of two concentric steel pipe piles flexibly connected by a special driving shoe, allowing for an air gap between the two tubes. The double-walled pile is driven into the sediment by using traditional equipment that strikes the inner pile only. The air gap between the inner and outer pile and the flexible coupling prevent the radial deformation wave produced by the pile hammer from interacting with the water and the sediment. Comparing the measurements from the double wall test pile and the control pile showed a reduced peak pressure (8.7–13.5 dB), RMS pressure (8.8–12.7 dB), and SEL (7–10.3 dB) (Dahl et al. 2016).

The mandrel-driven pile is much like a double wall pile; however, the inner pipe is removable. Comparing the measurements from the mandrel test pile and the control pile showed a reduced peak pressure (11.4–14 dB), RMS pressure (10.8–12.6 dB), and SEL (9.3 and 11.1 dB) (Dahl et al. 2016).

Fabric barriers have also been used to attenuate SPLs from pile driving activities. The theory is somewhat the same as for an air bubble curtain, in that the goal is to change the local impedance of the water that noise must travel through. Cofferdams can be used as well, and may be applied either full of water or drained to the mudline. Cofferdams full of water provide only limited attenuation, while dewatered cofferdams may provide the best isolation of the driven pile (Thorsen and Reyff 2003).

WSDOT monitoring has revealed significant variability in the attenuation achieved by different projects and also between different attenuation devices. The results of this research are depicted in Tables 7-22 through 7-25 below.

Table 7-21. Range, mean, and standard deviations for sound attenuation rates for unconfined bubble curtains achieved on WSDOT projects.

Location	Range (dB)	Mean (dB)	Standard Deviation (dB)
Friday Harbor	0-5	2	2.2
Bainbridge Island	3-14	7	4.7
Cape Disappointment	6-17	11	4.9
Mukilteo	7-22	15	10.6
Anacortes	3-11	8	3.1
SR 520	3-32	20	11.1
SR 529	16-26	22	4.3

Table 7-22. Range, mean and standard deviations for sound attenuation rates for confined bubble curtains achieved on WSDOT projects.

Location	Range (dB)	Mean (dB)	Standard Deviation (dB)
SR 24 – Yakima River	0-5	3	3.5
Eagle Harbor Maintenance Facility	1-3	2	1.4
SR 411 – Cowlitz River	4-9	7	2.6
SR 520 Test Pile Project	34-38	36	2.8

Table 7-23. Range, mean and standard deviations for sound attenuation rates for TNAP/DNAP achieved on WSDOT projects.

Location	Range (dB)	Mean (dB)	Standard Deviation (dB)
Mukilteo Test Pile Project (TNAP)	7-21	15	5.9
SR 520 Test Pile Project (DNAP)	11	11	n/a
Vashon Test Pile Project (modified TNAP)	9-13	11	2.1

Table 7-24. Range, mean, and standard deviations for different sound attenuation technologies.

Attenuation Technology	Range (dB)	Mean (dB)	Standard Deviation (dB)
Unconfined Bubble Curtain	0-32	11.9	8.7
Confined Bubble Curtain	0-38	12.1	13.8
DNAP/TNAP	7-21	12/7	4.4

Tables 7-26 through 7-28 show the noise reductions achieved for various WSDOT projects, pile diameters, substrate types, and hammer energy ratings since 2005. What is apparent from these tables is that there is significant variation in noise reduction achieved from different attenuation devices and at different locations. To be as accurate as possible in your calculations, when stipulating assumed noise reduction in biological assessments, it is imperative to select site specific data or surrogate data from a site with similar characteristics and/or similar attenuation devices used. Also, rather than using a single value to represent noise reduction, analyzing a range of values, or a high and low value is more accurate.

Recent research has demonstrated that sound pressure waves generated by impact pile driving will travel down the pile, enter the substrate and then travel back up and out of the substrate at a different angle, entering the water column outside of the bubble curtain (Reinhall and Dahl 2011). These sound pressure waves will not be attenuated and are a major factor in some of the variability observed in the effectiveness of the bubble curtains. Because of the large variability in the effectiveness of bubble curtains (and fabric barriers), there is no standard rate of attenuation assumed. Projects may either state their expectation of bubble curtain performance for use in the analysis, taking into consideration the variability described above, or a rate of effectiveness may be determined through the consultation itself. If the BA states an expected performance level (thereby making that level part of the project description), the author should coordinate with acoustics experts to determine a realistic performance standard for the specific project that takes into consideration the proposed attenuation technology and site conditions. If the level of attenuation that is assumed during the consultation is not achieved by the project, the project may be required to shut down until re-initiation of consultation is complete. It is therefore critical to assume a level of attenuation that is attainable.

Table 7-25. Noise reduction values for all Washington State DOT projects from 2005 to 2009 for steel piles of different diameters using an unconfined bubble curtain.

Location	Pile Diameter (inches)	Substrate Type	Hammer Energy Rating (ft-lbs) [a]	Date	Pile #	Average Noise Reduction per Pile (dB)
Friday Harbor Ferry Terminal	24	Silty sand with hard clay layer	60,000	2/10/05	1	5
				2/23/05	4	0
				2/24/05	5	1
	30	Silty sand with hard clay layer	60,000	3/4/05	8	3
Bainbridge Island Ferry Terminal	24	Sand and Fist-sized rocks to 1-foot rocks	55,000	10/18/05	1	14
					2	10
				10/20/05	3	7
					4	3
					5	3
Cape Disappointment Boat Launch Facility [b]	12	Silt and mud with glacial till layer	52,000	12/13/05	1	6
				12/14/05	2	14
					3	11
					4	17
					5	6
Mukilteo Test Pile Project	36	Sand and silt	164,000	11/16/06	R2	7
					T2	22
Anacortes Ferry Terminal	36	Sand and Silt Mix	165,000	1/17/07	1	11
					2	11
				1/19/07	4	5
					5	10
					6	8
					7	3
					8	9
SR 520 Test Pile Project	24	Very loose unconsolidated silt overlying glacial till	20,100	10/27/09	PB-1	11
					PB-2	3
					PB-3	26
					PB-4	28
	30			10/29/09	WAB2	32
					WAB5	19

Table 7-26 (continued). Noise reduction values for all Washington State DOT projects from 2005 to 2009 for steel piles of different diameters using an unconfined bubble curtain.

Location	Pile Diameter (inches)	Substrate Type	Hammer Energy Rating (ft-lbs) [1]	Date	Pile #	Average Noise Reduction per Pile (dB)
SR 529 Ebey Slough Bridge Replacement Project	72	Deep loamy silt	327,222	1/6/11	4	16
					5	22
				1/11/11	3	24
					6	26

[a] Actual energy used during operation of impact hammer is approximately 50% to 70% of this maximum energy for most piles. All hammers are diesel.

[b] These piles had steel wings that linked the piles together and pile caps were used between the pile and the hammer which possibly increased the number of total strikes per pile.

Table 7-26. Noise reduction values for all Washington State DOT projects from 2005 to 2009 for steel piles of different diameters using a confined bubble curtain.

Location	Pile Diameter (inches)	Substrate Type	Hammer Energy Rating (ft-lbs)[a]	Date	Pile #	Average Noise Reduction per Pile (dB)
SR 24 – Yakima River	24	Large 1-to 3-foot diameter boulders (riprap) with river rock and gravel below	60,000	June 2005	3	0
					5	5
Eagle Harbor Maintenance Facility	24	unknown	164,000	October 2005	1	7
					3	4
SR 411 Cowlitz River	24	Silty sand	72,900	July-August 2006	4	8
					7	4
					8	9
SR 520 Test Pile Project	30	Very loose unconsolidated silt overlying glacial till	20,100	October 2009	WAB1	38
					WAB4	34
Wahkiakum County Ferry Terminal (Columbia River)	18	Sandy silt	75,940	January 2010	1	0
					2	3
					3	3
					4	0
					5	13

[a] Actual energy used during operation of impact hammer is approximately 50% to 70% of this maximum energy for most piles. All hammers are diesel.

Table 7-27. Noise reduction values for all Washington State DOT projects from 2006 to 2009 for steel piles of different diameters using a Temporary or Double Walled Noise Attenuation Pile (TNAP or DNAP).

Location	Pile Diameter (inches)	Substrate Type	Hammer Energy Rating (ft-lbs) [a]	Date	Pile #	Average Noise Reduction per Pile (dB)
Mukilteo Test Pile Project (TNAP1) [b]	36	Sand and silt	164,000	11/16/06	R4	7
				2/19/07		15
Mukilteo Test Pile Project (TNAP2) [c]	36	Sand and silt	164,000	11/16/06	R3	21
					R1	17
SR 520 Test Pile Project (DNAP) [d]	30	Very loose unconsolidated silt overlying glacial till	20,100	10/29/09	WAB3	11
Vashon Test Pile Project (modified TNAP) [e]	30	Silty Sand	164,620	11/17/09	P-14	9
					P-10	9
				11/18/09	P-16	13
					P-8	12

[a] Actual energy used during operation of hammer is approximately 50% to 70% of this maximum energy for most piles. All hammers are diesel.

[b] TNAP1 (Temporary Noise Attenuation Pile) is a hollow walled steel pile casing placed around the pile being driven. Hollow cavity accidentally filled with water during installation, thus substantially reducing its potential effectiveness. The TNAP1 was repaired and retested on 2/19/07.

[c] TNAP2 is a steel pile with a 2-inch thick closed cell foam lining on the inside of the pile and a perforated metal screen on the inside of the foam.

[d] DNAP is a steel casing with a 1-inch air space and 4 inches of insulation and an inner steel casing sealed together at the top and bottom.

[e] Modified TNAP is a hollow steel casing with a 2-inch foam-filled hollow wall and a bubble ring on the inside at the bottom but only sealed at the bottom.

Impact driving in the dry can also generate underwater noise in adjacent aquatic habitats. Sound flanking occurs when a pressure wave travels down the pile, is transmitted into the soil, and then travels back up through the soil and into the water column. Pile driving in the dry is a minimization measure designed to reduce the amount of sound that is transmitted through the water. Currently, we have an approved method for calculating transmission loss from pile driving in the air and a method for calculating transmission loss from pile driving in the water. There is no method for calculating transmission loss through soil outside of the water, and then calculating the loss in the water. What we don't know is how much transmission loss occurs within the soil – the assumption is that it is greater than what occurs in water or air due to the denseness of the soil. We know that soil type - density and composition can affect transmission loss. It is impossible to predict what the transmission loss in soil will be and what the sound level will be at when it enters the water column. We have monitored a very few piles that have been driven in the dry; adjacent to or within the OHWM of a river. This includes H-piles, 16-inch steel and 72-inch steel piles. In all cases the pile installation did not exceed the current thresholds (these reports are on the WSDOT website). Based on this information, driving in the dry is effective at minimizing the effects of sound in the water and protecting fish.

7.2.4 Determining the Extent of Underwater Project-Related Noise

The action area for a project is defined as the extent of the physical, chemical, and biological effects of the action. When considering the extent of the noise element of the action area, consider the underwater area through which noise will travel until it reaches background levels.

This section provides instruction on how to estimate the extent of underwater project-related noise to determine a component of a project's action area and to ascertain potential effects to listed species, relative to established biological thresholds for disturbance and injury. NOAA has developed guidance for estimating sound propagation for pile driving sounds relevant to marine mammals. This guidance is available on the web at: http://www.westcoast.fisheries.noaa.gov/publications/protected_species/marine_mammals/killer_whales/esa_status/characterize_sound_propagation_modeling_guidance_memo.pdf

7.2.4.1 Steps for Defining the Extent of Project-Related Noise

The following subsection provides instruction for determining the extent of project-related underwater noise to help define the action area; noting that noise is just one element of the project that must be considered when defining the action area.

A brief example of how one would use the concepts discussed above to define the extent of project-related underwater noise in the Yakima River is provided here.

- Assume that a typical unattenuated peak noise level produced by driving a steel pile with a diesel hammer is 195 dB_{RMS} at a distance of 10 meters (33 feet) from the pile. Also assume a log (R) coefficient of 4.5 dB per doubling of distance (practical spreading model).

  Calculations used by the Services for determining at what point the project noise becomes indistinguishable from background sound assume a 4.5 dB decrease with each doubling of distance. At this rate of loss, the noise level from the source described above declines to the broadband background conditions of 140 dB_{RMS} – assuming the water body is a shallow, fast moving river at 46,416 meters (29 miles). $R_1 = R_2 * 10^{((195-140)/15)}$. However, in river systems, bends in the river or gravel bars are usually encountered well before this distance is reached, effectively reducing the extent of the action area. As mentioned above, temperature gradients, bottom topography, and currents can cause noise levels to attenuate more quickly. Therefore, it is often difficult to accurately determine the extent of noise using a standard geometric spreading model.

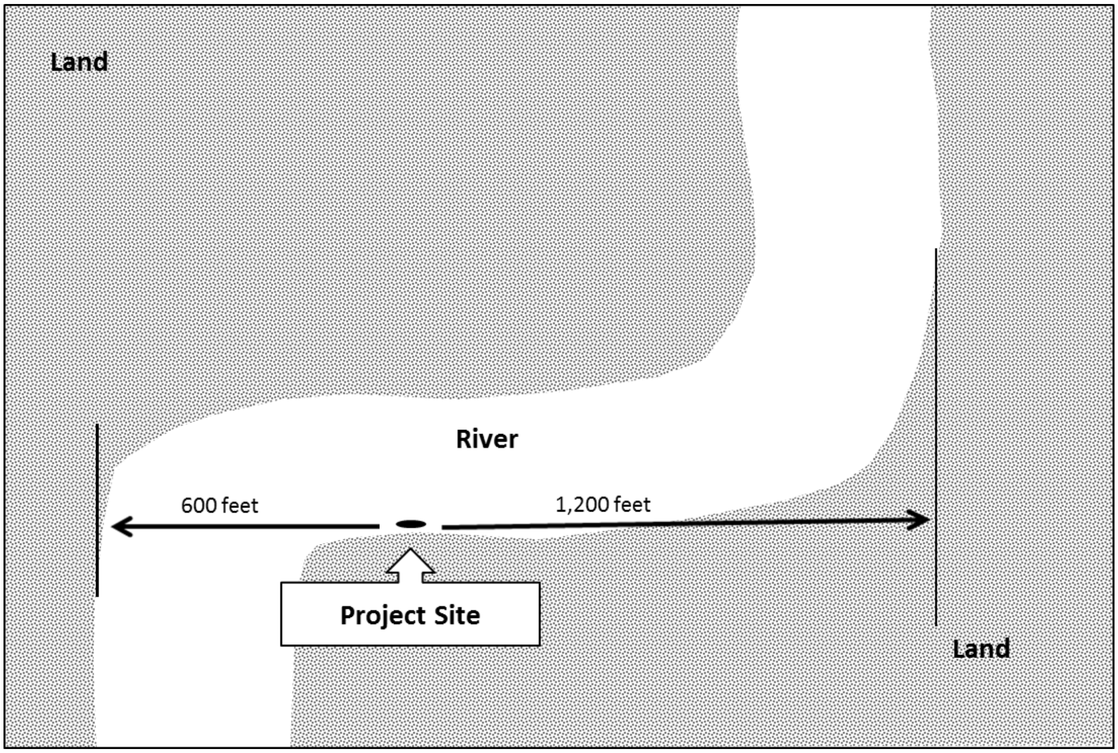

Figure 7-8. Example showing extent of underwater project-related noise in a river.

- Broadband background data is used to determine the action area in freshwater systems for projects that are not conducting marine mammal ESA or MMPA consultations.
- In addition, the use of a bubble curtain can reduce the levels at the source. Assuming a 3 dB reduction at the source described above from use of a confined bubble curtain (based on 0-5 dB range of reduction documented in the Yakima River data provided above), the distance at which the underwater noise reaches an ambient level (140 dB_{RMS}) is reduced to 5,455 meters (3.4 miles), an 88 percent reduction of the noise extent. Again, assess river sinuosity to determine if bends in the river could truncate the distance sound travels. In this case, a bend in the channel is present 600 feet upstream of the project and 1,200 feet below – so the extent of the project-related noise area would be confined to the 1,800-foot reach of river between these two river bends.

Remember, when completing a freshwater in-water pile installation consultation, the action area should be calculated using the broadband background number (in RMS) to calculate the furthest extent of effects of the project. For example: at the estimated the lowest daytime dB_{RMS} for background sound in a river system is 140 dB_{RMS} – thus the project would calculate how far out the sound generated by the pile with the highest source number would travel until it is indistinguishable from the background level of 140dB_{RMS}.

Broadband noise can also be used in marine mammal ESA and MMPA consultations to determine the extent of project-related noise where background data is not available by frequencies which match the marine mammal functional hearing groups. Background data is available by hearing frequency groups for several locations in Puget Sound (Table 7-13). It may not be available in other marine waters like Grays Harbor or Willapa Bay. In the absence of any background sound data, the acoustic effect thresholds established by NOAA, and described in section 7.2.4.4 *Threshold Levels*, can also be used to define areas of potential sound effects for marine mammal consultations and permitting efforts.

When completing a marine or estuarine in-water pile installation consultation, the action area should be calculated using the lowest reported background number (ideally frequency-weighted background noise data is available for different functional hearing groups) to calculate the furthest extent of effects of the project. For example: at Seattle the lowest daytime dB_{RMS} for background sound is $107dB_{RMS}$ for high-frequency cetaceans – thus the project would calculate how far out the sound generated by the pile with the highest source number would travel until it is indistinguishable from the background level of $107dB_{RMS}$. Note that if both vibratory and impact hammering will occur, the highest source number would be used to determine the extent of potential effects. It is most likely that the project-generated will encounter land before the calculated distance is reached. As a rule of thumb – the higher the source number, and the lower the background number, the greater the extent of effects.

An example of how action area would be determined for a marine in-water pile consultation at the Seattle Ferry Terminal is provided below:

- Impact pile driving of 36-inch steel piles, which will produce the greatest noise levels, has been measured at 210 dB_{peak} (193 dB_{RMS}) at 32.8 ft (10 m) from the source. A bubble curtain or similar noise attenuation device will be employed during impact pile driving. The effectiveness of bubble curtains varies widely but they have proven more effective in softer sediments such as those that exist at the Seattle Terminal. Average noise reduction for unconfined bubble curtains (Table 7-23) employed in similar environments is 12 dB; for this BA bubble curtains have been estimated to reduce noise levels by at least 10 dB to produce peak noise levels of 200 dB_{peak} (183 dB_{RMS}). Underwater noise levels will be monitored during impact pile driving.

- Background underwater noise levels at the Seattle Terminal were measured as broadband (120 dB_{RMS}) and within different frequency ranges. The lowest frequency weighted background noise level was in the 60Hz to 20kHZ range and would therefore be the frequency used to calculate the action area. Underwater noise levels within this range were $107dB_{RMS}$ (Table 7-13).

Using the practical spreading model $R1 = R2 * 10^{((183-107)/15))}$ the 183 dB_{RMS} generated by impact pile driving of 36-inch diameter steel piles would attenuate to the background level at approximately 87 miles from the source when using 107dB_{RMS} as the background sound level. However, the transmission of sound waves will be blocked by Bainbridge Island and West Seattle (Figure 7-9).

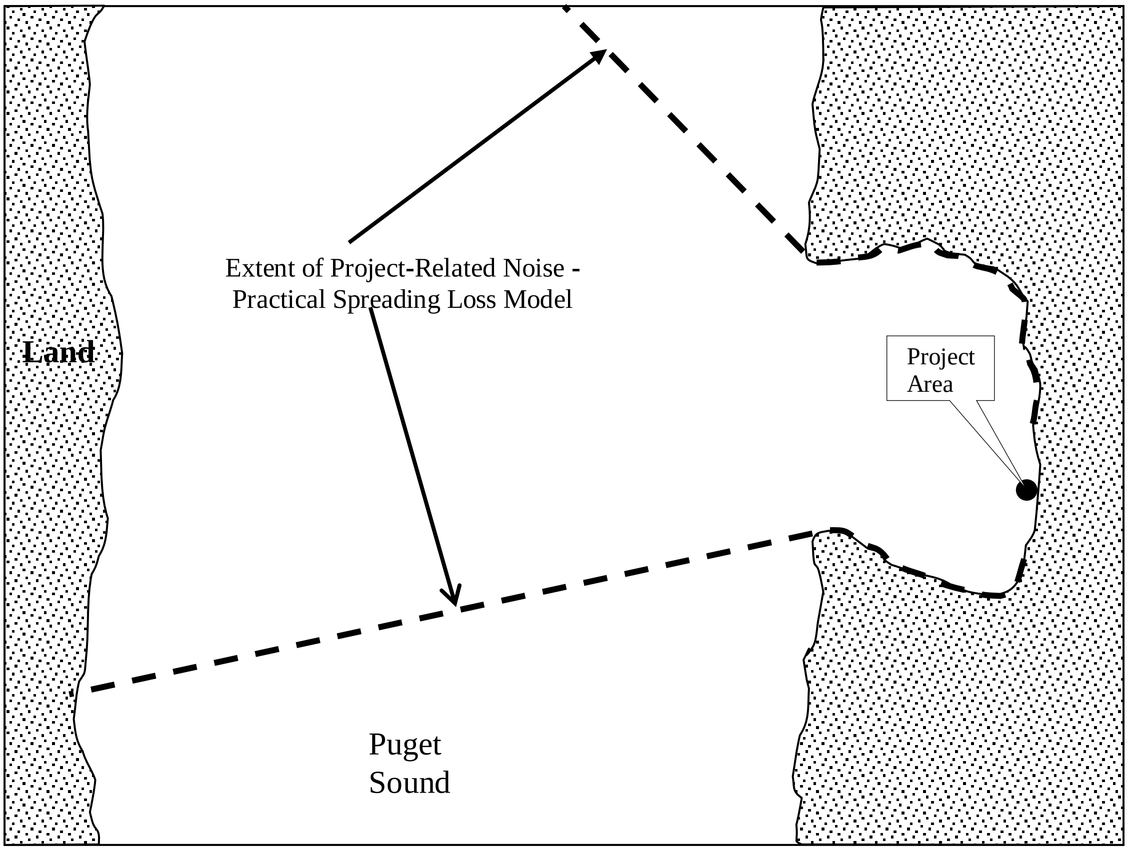

Figure 7-9. Example showing extent of underwater project-related noise from Elliot Bay to Bainbridge Island from Seattle Ferry Terminal Project.

7.2.4.2 Species and Noise

As is stated in the first section of this chapter, one task the project biologist must complete is identifying and measuring noise to determine the noise element of the action area. Another task the project biologist must complete is analyzing the effects of noise on the species that are addressed in the BA. Information and guidance to complete this task are provided in the sections below.

7.2.4.3 How Aquatic Species Hear

Fish – Hearing

The main sensory organ in fish is the lateral-line system that detects low-frequency (<100 Hz) particle motion in water. The lateral-line organ is likely involved in acoustic repulsion when the source is within a few body lengths of the fish. The inner ear located within the skull of the fish is sensitive to vibration rather than noise pressure.[4] In fish species that are hearing specialists, the gas-filled swim bladder acts as a transducer that converts noise pressure waves to vibrations, allowing the fish to detect noise and vibration.

Fish species with no swim bladder, or a small one, tend to have a relatively low auditory sensitivity. Fish having a fully functional swim bladder tend to be more sensitive. Fish with a close coupling between the swim bladder and the inner ear are most sensitive.

Most audiograms of fishes indicate a low threshold (higher sensitivity) to noises within the 100 Hz to 2 kHz range (Stocker 2002) (Figure 7-10).[5] Anderson (1992) suggests that juvenile fish may have less developed hearing abilities so the distance at which they could detect pile driving noises might be much less than adults. Audiograms developed for various fish species are based on noise pressure. However, fish do not hear with noise pressure. They hear with particle motion. Therefore, the thresholds and frequency ranges listed above and in Figure 7-11 will likely be revised when those data are available.

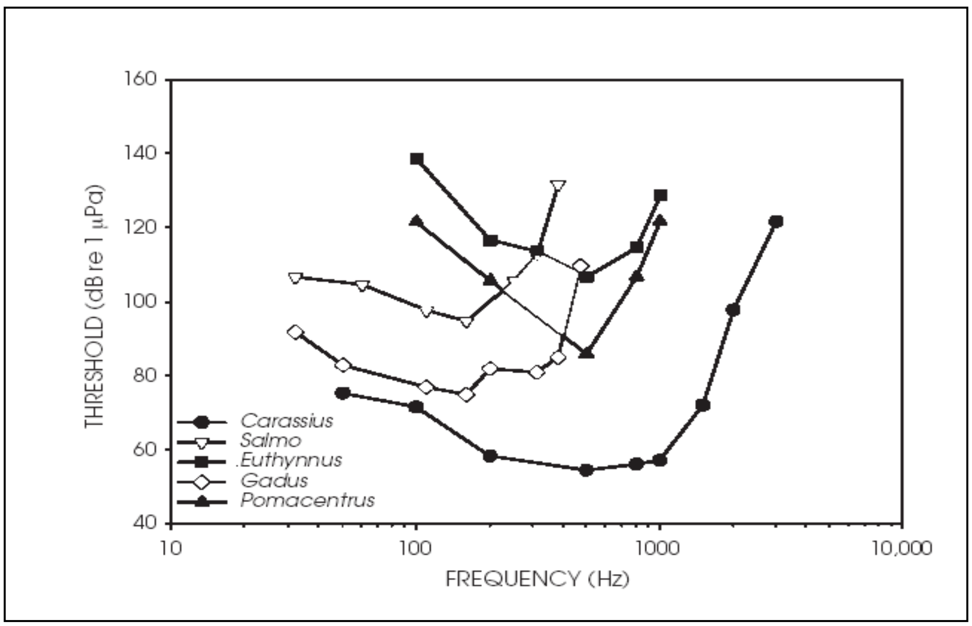

Figure 7-10. Audiogram for several fish species.

Source: Burgess and Blackwell (2003).

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[4]. Fish have three symmetrically paired structures in the inner ear associated with bony otoliths: the lagena, sacculus, and utriculus. In most species, the saccule and lagena detect acoustic pressure and acoustic particle motion (Popper and Fay 1973) and the utricle is involved in sound detection by several species of clupeids and perhaps other species (Popper and Fay 1993).

[5]. Cod have a hearing threshold of 75-80 dB_{RMS} between 100 and 200 Hz (Chapman and Hawkins 1973). Atlantic salmon have a sensitivity of 95 to 100 dB_{RMS} between 100 and 200 Hz (Hawkins and Johnstone 1978). Since both species are most sensitive between 100 and 200 Hz one would expect to see damage to salmon occurring with exposure to continuous sound at about 200 dB_{RMS} (Hastings 2002).

High-intensity noises may temporarily or permanently damage the hearing of fish.[6] Temporary hearing damage is referred to as a temporary threshold shift and permanent hearing damage is referred to as a permanent threshold shift. However, damage to hearing by intense noise depends on auditory thresholds and will thus vary from species to species (Popper and Fay 1973, 1993).[7] Popper et al. (2005) exposed three species of fish to noises from a seismic airgun, having noises similar to pile driving. Peak noise levels ranged between 205 and 209 dB. They exposed a hearing generalist (broad whitefish), a hearing specialist (lake chub), and a species that is intermediate in hearing (northern pike). They found that the hearing generalist had no significant effects from air gun exposure; the lake chub indicated the most effect in temporary threshold shift, and the northern pike showed a significant hearing loss but less than that of the lake chub. Lake chub and northern pike returned to their respective normal thresholds after 18 to 24 hours.

One study completed by Feist et al. is particularly pertinent to species potentially occurring in Washington. Feist et al. (1992) looked at the effects of concrete pile driving activities on the behavior and distribution of juvenile pink and chum salmon in Puget Sound. The authors found that juvenile pink and chum salmon (1 to 2 inches total length) did not change their distance from shore or cease feeding in response to pile driving. However, they did find that there were substantial differences in the distributions and sizes of fish schools on pile-driving days versus non-pile-driving days.

Fish: Lethal Impacts Associated with Noise

Risk of injury or mortality for aquatic species and fish associated with noise, in general, is related to the effects of rapid pressure changes, especially on gas filled spaces in the body. Rapid volume changes of the swim bladder may cause it to tear, reducing hearing sensitivity in some hearing specialist species, and loss of hydrostatic control.

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[6]. Popper and Clarke (1976) found that goldfish (*Carassius auratus*) demonstrated up to a 30 dB decrease in hearing sensitivity when exposed to 149 dB for 4 hours, but hearing returned to normal after 24 hours. Enger (1981) used a sound level of 180 dB to destroy bundles of cilia on the saccular maculae of codfish as evidenced by scanning electron microscopy and assumed permanent hearing loss.

[7]. Enger (1981) exposed 26 cod (*Gadus morhua*) to continuous tones of 180 dB_{RMS} at frequencies from 50 to 400 Hz for 1 to 5 hours and found destruction of auditory cilia cells in the saccule. Hastings (1995) found destruction of auditory sensory cells when she and her colleagues exposed goldfish (*Carassius auratus*) to continuous tones of 189, 192, and 204 dB_{peak} at 250 Hz and found destruction of ciliary bundles correlate with sound pressure level at a 95% confidence level. Hastings et al. (1996) found destruction of sensory cells in the inner ears of Oscars (*Astronotus ocellatus*) four days after being exposed to continuous sound for 1 hour at 180 dB_{peak} and 300 Hz. Fish exposed to 180 dB_{peak} sounds at 60 Hz either continuous or 20% duty cycle (impulsive) or to 180 dB_{peak} sounds at 300 Hz and 20% duty cycle for 1 hour had no apparent damage. The authors also found no damage in fish allowed to survive for only 1 day after exposure, suggesting that damage may develop slowly.

Hastings et al. (1996) also examined the sensory cells of the lateral line and semicircular canals of the inner ear in the Oscars and found no damage. The authors speculated that this could be related to the fact that these sensory cilia cells do not have an overlying otolith.

McCauley et al. (2003) exposed caged pink snapper (*Pagrus auratus*) to air gun sound levels as the ship passed by the caged fish, producing damaged cilia cells that did not regenerate up to 58 days after exposure.

According to Hardyniec and Skeen (2005) and Hastings and Popper (2005) the effects of underwater noises created by pile driving on fish may range from a brief acoustic annoyance to instantaneous lethal injury depending on many factors including:

- Size and force of the hammer
- Distance of the fish from the pile
- Depth of the water around the pile
- Depth of the fish in the water column
- Amount of air in the water
- The texture of the surface of the water (amount of waves on the water surface)
- The bottom substrate composition and texture
- Size of the fish
- Species of the fish
- Physical condition of the fish

Physostomus fishes, such as salmonids, regulate the air in their swim bladders through a direct connection to the esophagus. Salmonids acclimate their swim bladders by gulping air at the surface, and as they swim deeper the swim bladder becomes compressed. When exposed to a sudden positive pressure, or overpressure, the swim bladder compresses further. When exposed to a sudden negative pressure, or underpressure, the swim bladder may expand beyond its original volume at depth but may not suffer or injure any other organs because it has some room to expand. Physostomus fishes acclimated to the surface atmospheric pressure may suffer less injury or mortality the deeper they are in the water column, whereas those acclimated to deeper water pressure may suffer more injury near the surface or in shallow areas (Abernethy et al. 2003).

Physoclistus fishes, such as bluegill, regulate air in the swim bladder through the circulatory system. In a physoclistus fish, the swim bladder will roughly maintain its volume at depth. During exposure to underpressure, the swim bladder will expand, possibly tearing and causing damage to other organs. The magnitude of the expansion of the swim bladder is dependent on the magnitude of the underpressure. It functions according to Boyle's law: The volume of a confined amount of gas at constant temperature is inversely proportional to the pressure applied to the gas.

There have been a few studies addressing the effects of pile driving on fish, which are described here, and others are summarized in the footnotes.[8] Illingworth and Rodkin (2001) found that there was not only a relationship between distance from the pile but an increase in the degree of damage and number of fish impacted with increasing duration of exposure to pile-driving activities.[9] Illingworth and Rodkin (2001) found that both a smaller hammer size and bubble curtains reduced injuries to fish.[10] In the literature review by Hastings and Popper (2005) they found that the study by Yelverton et al. (1975) using underwater explosives indicated that smaller fish were more likely to be harmed than larger fish during underwater explosions.

Fish: Behavioral Impacts Associated with Noise

Mueller et al. (1998) and Knudsen et al. (1992; 1997) found that juvenile salmonids (40 to 60 mm length) exhibit a startle response followed by a habituation to low frequency (infrasound) in the 7 to 14 Hz range. Mueller et al. (1998) and Knudsen et al. (1992, 1997) also indicate that noise intensity level must be 70 to 80 dB above the hearing threshold at 150 Hz to obtain a behavior response.

According to Feist et al. (1992) broad-band pulsed noise (pile driving noise) rather than continuous, pure tone noises are more effective at altering fish behavior. However, the noise level must be at least within the minimum audible field of the fish for the frequencies of interest (1 to 100 Hz for pile driving). Ambient sound should be at least 24 dB less than the minimum audible field of the fish, and the pile driving noise levels had to be 20 to 30 dB higher than ambient sound levels to produce a behavioral response (in herring) (Olsen 1969, 1971).

Behavioral sensitivity is lowest in flatfishes that have no swim bladder and also in salmonids (brown trout) in which the swim bladder is present but somewhat remote from the inner ear. Gadoid fishes (cod, whiting) in which the swim bladder is closely associated with the inner ear display a relatively high sensitivity to noise pressure (Turnpenny et al. 1994).

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[8].

Experiments conducted by the Pacific Northwest National Laboratory (PNNL) placed bluegill in a hyperbaric chamber and acclimated one group to simulated ambient surface pressures of 101 kilopascals (kPa) and another group to simulating ambient pressures at 30 foot depth of 191 kPa inside a hyperbaric chamber. The fish were then exposed to 400 kPa for 30 to 60 seconds followed by rapidly decreased pressure to 2 and 10 kPa respectively within 0.1 seconds. The fish were then held for 48 hours for observation. The results for bluegill indicated 90% injury and 21% mortality to the 30 foot acclimated group and 35% injury and 5% mortality to the surface acclimated group (after 48 hours). Abernethy et al. (2003) found that both acclimation (Pa) and exposure (Pe) pressures are important and the ratio of Pe to Pa is an important predictor to mortality and possible injury. Similar unpublished work has been done with rainbow trout and results indicated no mortality and minimal injury (Abernethy et al. 2003).

[9]. In one experiment, all fish exposed to pile driving for one minute were unaffected while 80 percent of fish exposed for 6 minutes exhibited significant tissue damage. In a second experiment, only fish exposed for 40 minutes or longer were seriously injured.

[10]. The authors put fish in cages at various distances from 8-foot diameter steel piles, and 60% of fish were found with damage to their internal organs as far as 150 meters (492 feet) from the pile driven by the large hydraulic hammer (1,700 kJ maximum) and no bubble curtain. With a smaller hydraulic hammer (750 kJ maximum) and a bubble curtain in operation, only 40% were damaged at this distance. In general, the greatest impacts were observed within a 30-meter (98-foot) radius of the pile. It is assumed that there would be a decrease of 3 dB with halving of the hammer energy.

Hastings and Popper (2005) present a summary of different noise levels and effects on fish based on a review of the best available science from the literature that has the most relevance to pile driving. However, the review does not include Pacific Salmon species or bull trout, the species project biologists would need to address in their BAs.

Jorgensen and Gyselman (2009) from Fisheries and Oceans Canada suggest that the noise generated by an air gun at noise levels between 205 and 209 dB_{peak} indicated no significant difference in startle response in the vertical direction or vertical velocity and a possible slight difference in the horizontal direction. The author also indicated that observed fish did not actively avoid the noise, and there appeared to be no hearing loss. The fishes studied included broad whitefish, northern pike, and lake chub.

Hearing – Marine Mammals

Different taxa of marine mammals are sensitive to different frequencies of sound. An excellent summary of the hearing frequency ranges for species occurring in the Pacific Northwest is available on the WSDOT website: http://www.wsdot.wa.gov/NR/rdonlyres/AE439D96-BD72-4D1E-BB99-0C8E228E0F13/0/BA_MarineNoiseFrequ.pdf. For small toothed whales (suborder Odontoceti), such as killer whale, studies of hearing have generally been conducted on a few individuals of some species. Therefore, individual variation within a species may not be represented in the results. No studies of baleen whales (suborder Mysticeti) have been conducted.

Killer whales are considered a mid-frequency cetacean, and have an estimated auditory bandwidth of 50Hz to 100 kHz and are most sensitive around 20 kHz (Szymanski et al. 1999, as cited in 76 FR 4300). In a review by Au and Hastings (2008) the audiogram shape, level of maximum sensitivity, and high-frequency limits of the killer whale were similar to other small odontocetes tested.

Humpback whales, like all baleen whales, are low-frequency cetaceans. Because no direct measurements of auditory capacity have been conducted for these large whales, hearing sensitivity for low-frequency whales has been estimated by Southall et al. (2007) from various studies or observations. A generalized estimate of an auditory bandwidth of 7 Hz to 22 kHz for all baleen whales is cited in Southall et al. (2007) from Ketten et al. 2007.

Pinnipeds communicate both on land and underwater. Both in-air and in-water pinniped audiograms are similar to typical mammalian audiograms; there is a low-frequency region that increases in sensitivity with frequency, a high-sensitivity dip at mid frequencies, and a high-frequency region in which sensitivity decreases rapidly with frequency (Au and Hastings 2008). Underwater hearing studies have been conducted on several species of pinnipeds but not on Steller sea lions. Studies conducted on California sea lions (in the same family as Steller sea lions, Otariidae) found the range of maximal hearing sensitivity is between 1 and 28 kHz, functional high frequency hearing limits are between 35 and 40 kHz, with peak sensitivities from 15 to 30 kHz (Schusterman et al. 1972, as cited in 76 FR 4300). At lower frequencies (below 1 kHz) sounds must be louder to be heard (Au and Hastings 2008; Kastak and Schusterman

1998, as cited in 73 FR 41318). As previously stated, studies of hearing have generally been conducted on a few individuals. Therefore, individual variation within a species may not be represented in the results.

Southall et al. (2007) designated a functional hearing group for pinnipeds and estimated the lower and upper frequencies of the groups. The phocid pinnipeds (seals) functional hearing group has a frequency range between 75 Hz and 20 kHz. The otariid pinnipeds (eared seals) functional hearing group has a frequency range between 100 Hz and 20 kHz. Studies indicate that pinnipeds are sensitive to a broader range of sound frequencies in water than in air (Southall et al. 2007).

Marine Mammals: Impacts Associated with Noise

Marine mammals produce sounds in various contexts and use sound for various biological functions including social interactions, foraging, orientation, and predator detection. Interference with producing or receiving sounds could have negative consequences including impaired foraging efficiency from masking, altered movement of prey, increased energetic expenditures, and temporary or permanent hearing threshold shifts due to chronic stress from noise (Southall et al. 2007).

Marine mammals, like other mammals, can experience a masking effect from noise exposure. Masking occurs when environmental noise is loud enough to cover or mask other noises. However, unlike other mammals and pinnipeds, toothed whales echolocate and communicate by ultrasonic pulsed calls, whistles, and clicks. Their highly developed acoustic ability is used for navigation, prey location, and communication. Noise can mask echolocation and impede communication necessary for cooperative foraging (Bain and Dahlheim 1994). Masking decreases the area where prey items are detectable by echolocation. Masking is most acute when the noise source is directly in front of killer whales (Bain and Dahlheim 1994).

Exposure to chronic or high levels of sound may result in physiologic effects to hearing or, in extreme cases tissue damage or stranding. Temporary threshold shift (TTS) occurs when the auditory system is exposed to a high sound level over a duration that causes the cochlear cilia cells to fatigue and results in an a temporary decrease in hearing sensitivity. The hearing sensitivity returns when the cilia cells return to their normal shape (Au and Hastings 2008). Permanent threshold shift (PTS) is the term used when hearing sensitivity is permanently altered from high levels of sound exposure due to damage of the cochlear cilia cells. High levels of sound exposure may result in hemorrhaging around the brain and ear bones (NMFS 2005b). Other results from intense acoustic exposure, such as naval sonar, may lead to stranding of cetaceans, either from behavioral reactions or injury.

A sound source's frequency compared to a species hearing frequency range, as well as the intensity and energy from the source that are received by an animal, affect the potential for sound to cause masking, a behavioral response, or physical injury. In addition, Southall et al. (2007) noted, that even in well-controlled studies, behavioral responses in marine mammals and conditions which elicit the response are highly variable and strongly dependent upon the context of exposure and by an individual subject's prior experience, motivation, and conditioning.

Marbled Murrelets: Impacts Associated with Noise

Exposure to increased sound pressures can result in adverse effects such as temporary auditory effects that do not result from physical injury, as well as changes in marbled murrelet behavior or barotrauma resulting in death. Non-injurious temporary threshold shifts in hearing (TTS) may cause masking, delayed or interrupted foraging, and interference with mate identification, bonding, and courtship.

Underwater Noise. There are no published studies specific to impact pile driving and its effect on marbled murrelets, or any other seabird. Data specific to seabirds is primarily limited to evaluations of the effects of underwater blasting and seismic testing (Cooper 1982; Flint et al. 2003; Lacroix et al. 2003; Stemp 1985; Yelverton and Richmond 1981).

Due to the lack of seabird specific data, a variety of other vertebrate species have been used to evaluate the effects of the high sound levels generated by pile driving on marbled murrelets. High levels of underwater sound are known to have negative physiological and neurological effects on a wide variety of vertebrate species (Yelverton et al. 1973; Yelverton and Richmond 1981; Gisiner et al. 1998; Hastings and Popper 2005). Experiments using underwater explosives found that rapid change in underwater SPLs resulted in internal hemorrhaging and mortality in submerged mallards (*Anas platyrynchos*) (Yelverton et al. 1973). During seismic explorations, it has been noted that seabirds were attracted to fishes killed as a result of the seismic work (Fitch and Young 1948; Stemp 1985). Fitch and Young (1948) found that diving cormorants were consistently killed by seismic blasts, and pelicans were frequently killed, but only when their heads were below water.

The potential for injury and/or mortality of any aquatic organism from pile driving depends on the type and intensity of the sounds produced. These are greatly influenced by a variety of factors, including the type of hammer, the type of substrate, and the depth of the water. Biologically, key variables that factor into the degree to which an animal is affected include size, anatomical variation, and location in the water column (Gisiner et al. 1998). Observation of foraging marbled murrelets during impact pile driving at one project in Washington revealed that marbled murrelets will come fairly close (within 300 m) to active pile driving operations and continue to dive and forage despite elevated underwater sound (Entranco Inc. and Hamer Environmental 2005).

Exposure to elevated SPLs can cause shifts in auditory thresholds. These shifts can be temporary (TTS) or permanent (permanent threshold shift) and decrease sensory capability. Ryals et al. (1999) documented hair cell loss in birds that experienced acoustic overexposure. Using scanning electron photomicrographs, the authors were able to show hair cell loss and damage on the surface of the papillae. Exposure to acoustic sources that involve loss and/or physical damage of hair cells is considered injury by the Service. In regard to auditory damage, the inner ear is most susceptible to trauma, although intense sounds can also damage the middle and outer ear (Gisiner et al. 1998). Not all frequencies of sound produce equivalent damage at the same exposure level, nor will the same frequency/exposure combination cause equivalent damage in all species (Gisiner et al. 1998). The severity of a threshold shift depends upon several factors such as the sensitivity of the subject, and the level, frequency, and duration of the sound (Gisiner et al. 1998). These effects are not completely understood, however, it is generally acknowledged that there is considerable variation within and between species, that for narrow-band noises, hearing loss centers around the exposure frequency, and that there is some combination of sound level and exposure time when hearing loss becomes irreversible (Saunders and Dooling 1974; Gisiner et al. 1998). The majority of studies [with cats and rodents (especially chinchilla)] used relatively long duration stimuli (greater than 1 hr.) and mid to low frequencies (1 to 4 kHz). These have noted that intensity and duration of exposure can act synergistically to broaden the extent of the hearing loss (Gisiner et al. 1998). Repeated exposure to sounds that produce TTS, without adequate recovery periods, can also induce permanent, acute, hearing loss (Gisiner et al. 1998). An organism that is experiencing TTS may suffer consequences of not being able to detect biologically relevant sounds such as approaching predators or prey, and/or mates attempting to communicate.

Threshold shift in birds was studied within lab settings by Ryals et al. (1999) and in pinnipeds by Kastak et al. (2005) revealing that threshold shift increased more in response to an increase in duration than compared to an increase in SPL. Birds tested under these lab settings generally demonstrate greater tolerance to high SPLs than other taxa. Although these findings are not completely understood, there is general agreement that: 1) considerable variation occurs in individual responses, within and between species; 2) hearing loss occurs near the exposure frequency (Hz) in organisms (for narrow-band sound); and 3) hearing loss becomes irreversible under some combination of sound pressure level and exposure time, even in birds (Saunders and Dooling 1974; Gisiner et al. 1998; Ryals et al. 1999).

Injuries from high underwater sound levels can be thought of as occurring over a continuum of potential effects ranging from a threshold shift in hearing to mortality. A threshold shift in hearing includes impaired or lost hearing. A threshold shift may be either temporary or permanent, depending on a number of factors, including duration pressure and loudness of the sound (National Institute of Health: < https://www.nidcd.nih.gov/health/noise-induced-hearing-loss > accessed December 29, 2016). The Marbled Murrelet Science Panel of experts, convened from July 27-29, 2011 in Lacey, Washington, determined that the onset of hair cell loss would occur at cumulative 202 dB SEL. However, temporary threshold shifts may occur at lower sound levels without resulting in physical injury to the individual. The severity of a threshold shift depends upon several factors such as the sensitivity of the subject, the received SPL, frequency, and duration of the sound (Gisiner et al. 1998). Proceedings from the panel are available at the USFWS website:
http://www.fws.gov/wafwo/pdf/MAMU_ConferenceSummaryReport_090711.pdf.

For fishes, a correlation between size and the impulse level needed to cause injury has been noted (Yelverton et al. 1975; Hastings and Popper 2005). This type of analysis has not been done for birds. However, Yelverton and Richmond (Yelverton et al. 1973; Yelverton and Richmond 1981) and Yelverton et al. (1973) noted mass of the birds used in their studies and gave charge size and range of blasts. The mean mass of the birds used was 1.16 kg for mallards and 2.33 kg for Rouen ducks. Marbled murrelets are smaller, averaging 0.22 kg. The smallest juvenile marbled murrelet recorded in the marine environment in Washington was 0.16 kg (Emily Teachout and T. D. Bloxton, pers. comm. September 10, 2010 as cited in USFWS 2011a). Given the correlations observed with fish and regarding size and impulse level, it was determined that marbled murrelets would be impacted by lower impulse levels than those identified for mallards and Rouen ducks (SAIC 2011).

The various threshold levels for injury and harassment of marbled murrelets that were determined by this expert panel are described in Section 7.2.4.4 in the *Marbled Murrelet Thresholds* subsection.

<u>In-air Noise in Marine Environments</u>. In 2013 the USFWS convened a second panel to focus on sound exposures that would induce behavioral changes that constituted harassment on marbled murrelets. Based on the result of that panel, USFWS shifted away from the underwater 183 dB SEL non-injurious threshold shift to a 29 dB spectrum level (SL) in air masking threshold. The masking threshold captures the concept that a noisy environment will result in impaired essential communication between foraging murrelets. Communication between foraging murrelets is considered to be the critical hearing demand for murrelets in a marine environment. The masking threshold is not applied to murrelets in terrestrial habitats. The 29 dB SL was derived from the received level of the murrelets keer call (60 dB), and the difference in sound levels required for detection and recognition above ambient. The USFWS did not have SL data for most pile types. To determine the area affected by masking, the USFWS evaluated data from the U.S. Navy and determined that for "typical" pile driving project, masking effects are considered insignificant. For "atypical" projects, the area affected for steel piles less than or equal to 36-inch diameter is approximately 42 meters, and for steel piles greater than 36-inch diameter it is approximately 168 meters. If SLs can be monitored during a project, and it is determined that they do not exceed 29 dB SL over any areas of open water, then monitoring would not be necessary. A typical pile driving project is defined as a project which vibes in the piles as much as possible before impact driving to proof the piles. The typical project also implements a crepuscular limited operating period during the murrelet nesting season (April 1 through September 23), which prohibits work from two hours prior to sunset, to two hours after sunrise. Typical pile driving projects are not expected to result in measurable effects to murrelets; therefore a masking monitor is not required. The lack of measurable effects from typical projects is expected because:

- Impact pile driving will be limited to two hours after sunrise to two hours before sunset during the nesting season so peak foraging periods will not be impeded;
- Proofing of piles is typically of short duration (<30 minutes) and is intermittent with long breaks between installation of each pile so that murrelets foraging during pile installation will be able to forage without impact pile driving noise;
- Murrelets may employ strategies to overcome masking effects that include vocal adjustments and these adjustments are expected to have neutral or insignificant energetic costs;
- Murrelets may compensate for some amount of masking effect by moving closer together, or by moving further from the noise source. The USFWS does not expect

these behavioral changes to have measureable effects to individuals for typical projects;

- The characteristics of murrelet vocalizations indicate they may be less affected by pile driving noise; they are likely adapted for maximum transmission because their foraging habitat includes natural sources of ambient noise (wind and waves).
- The duration of the most common murrelet vocalizations is long (~400 ms) compared to the length of individual pile strikes (~50 ms). Impact proofing is also intermittent, and some signals will be effectively transmitted during proofing. Short-term, intermittent interference with communication is not expected to result in measureable effects to individual murrelets.
- Observations of murrelets during impact pile driving show that they continue to forage during impact driving. The USFWS expects that these foraging attempts are at least partially successful (USFWS 2013b).

Under this analytical framework, atypical pile driving projects would be those that are either 1) not limiting impact pile driving to that needed for proofing; 2) a pile material other than steel; or 3) installation of piles larger than 36 inches in diameter (USFWS 2013b). These projects may be expected to implement the crepuscular limited operating period during the murrelet nesting season, and to conduct murrelet monitoring of the masking zone from the shore or an overwater structure.

The response of murrelets to the in-air masking effects of *atypical impact pile driving projects* may present a greater risk of creating measureable effects to individuals. Prolonged exposures may not be able to be mitigated by the factors described above, and may have additional effects not considered here. Below are some of the considerations needed for each type of “atypical” pile driving scenario:

- Impact-only Installation. Where projects do not propose to use a vibratory hammer as the primary installation method and reserve impact pile driving to that needed for proofing, the above analysis does not automatically apply. If impact driving is relatively constant, communication between foraging partners may be significantly impaired. Use of the diurnal timing restriction can help minimize potential impacts by protecting peak foraging periods.
- Piles >36” Diameter. Larger pile sizes may result in larger areas of effect, so the challenge with larger pile sizes is whether or not to expect exposure.
- Other Pile Materials. Spectrum level data are currently unavailable for pile types other than steel. It is unknown whether the spectrum level of a concrete pile is similar enough in frequency content and energy concentration to create similar masking effects. One could assume that the spectrum levels generated from concrete piles will pose the same risks for masking and apply this framework. Otherwise, project-specific analysis will be required (USFWS 2013b).

7.2.4.4 Threshold Levels

Fish Thresholds

Beginning in 2002, several studies made various recommendations for injury and behavioral effects thresholds for salmons. These recommendations have been modified over time and. based on recommendations of the Fisheries Hydroacoustic Work Group, in June of 2008, FHWA, WSDOT, the Oregon Department of Transportation, California Department of Transportation, Regions 1 and 8 of the USFWS, and the Northwest and Southwest Regions of NMFS reached agreement on the interim fish noise exposure thresholds.

The current interim thresholds for fish are as follows:

- 206 dB$_{peak}$
- 187 dB cumulative SEL for fish $\geq$ 2 grams
- 183 dB cumulative SEL for fish $<$ 2 grams

Where cumulative SEL (cSEL) is calculated as:

cSEL = SEL(single strike at ~10 meters from the pile) + 10 * log (# strikes).

The number of strikes is estimated based on how many strikes occur in a summation period. Typically, the summation period is a day and includes a break in pile driving for 12 to 18 hours. The break between summation periods allows fish to move out of the affected areas or time to recover from temporary threshold shifts. If the cumulative SEL threshold is exceeded in a summation period, physical injury to fish is possible. Whether or not physical injury occurs is dependent on the project, and site-specific factors, such as local habitat conditions, as well as species specific factors. One factor to consider is whether the fish being analyzed are stationary or are migrating through an area. It is important to note that NMFS assumes that single strike SELs below 150 dB do not accumulate to cause injury.

The 150 dB$_{RMS}$ guideline for potential behavioral effects may be considered in some consultations depending on location and the time of year in which the work is occurring. It is not included in every consultation. More research and discussions will be needed to get a better understanding of the behavioral component of the thresholds. It is impossible to mitigate pile driving noise levels below the 150 dB$_{RMS}$ level at this time. Sound pressure levels in excess of 150 dB$_{RMS}$ are expected to cause temporary behavioral changes, such as elicitation of a startle response, disruption of feeding, or avoidance of an area. Depending on site specific conditions, project timing, project duration, species life history and other factors, exposure to these levels may cause behavioral changes that rise to the level of "take". Those levels are not expected to cause direct permanent injury, but may indirectly affect the individual (such as impairing predator detection). It is important to note that this is a "may affect" threshold, not an adverse effect threshold. Whether or not 150 dB$_{RMS}$ causes take is dependent on consideration of numerous factors.

WSDOT has observed fish kills during some of its pile driving. Sound level measurements at the Mukilteo Test Pile Project (Laughlin, 2007) indicated that the estimated sound levels measured at the time of the fish kills were 209 dB_{peak}, 202 dB_{RMS}, and 183 dB SEL for a single strike. Many of the killed fish observed were pile perch.

A summary of thresholds for fish and marine mammals is available on the WSDOT website: http://www.wsdot.wa.gov/environment/technical/fish-wildlife/policies-and-procedures/esa-ba/preparation-manual

Marbled Murrelet Thresholds

The USFWS (2011b) has identified underwater threshold and guidance noise levels for foraging marbled murrelets. The guideline of 150 dB single strike SEL is now recognized by USFWS as effective quiet (EQ), wherein it is assumed that energy from pile strikes below this SEL does not accumulate to cause injury. USFWS also recognizes a behavioral guideline of 150 dB_{RMS}, an injurious auditory threshold of 202 dB SEL (permanent threshold shift in hearing due to permanent loss of cochlear hair cells), and a non-auditory injury (barotrauma) threshold of 208 db SEL. Whether or not *take* actually occurs at these levels is dependent on numerous factors as is mentioned above.

The USFWS has developed pile driving in-air noise masking guidance for foraging marbled murrelets. Masking can impinge important communication with conspecifics within 30 m of each other, concurrent with pile driving sound when the received level of the pile driving sound exceeds 29 dB (SL). The area of this effect will vary depending on source levels and ambient conditions. For most projects in Puget Sound, the USFWS has pre-determined potential masking zone dimensions for 36- and 24-inch diameter piles that are driven using a vibratory hammer, and proofed with an impact hammer. These would be considered "typical" projects if they also include timing restrictions during the murrelet nesting season (April 1 through September 23). Typical pile driving projects are not expected to result in measureable effects, and therefore, murrelet monitoring of masking zones is not required.

Masking may result in measureable effects to individual murrelets for "atypical" projects. These projects will require project specific analysis and a determination as to whether this analysis applies, and will need to be made in coordination with the USFWS (see the discussion on pages 7-68 to 7-70). Atypical projects will generally require nesting season timing restrictions and monitoring of the masking zone.

A summary of these thresholds is available on the WSDOT website: http://www.wsdot.wa.gov/environment/technical/fish-wildlife/policies-and-procedures/esa-ba/preparation-manual

Marine Mammal Thresholds

In 2016, NMFS published comprehensive technical guidance on sound levels likely to cause injury and behavioral disturbance in the context of the ESA and Marine Mammal Protection Act

(MMPA). The guidance and thresholds are available at: http://www.nmfs.noaa.gov/pr/acoustics/guidelines.htm This guidance was revised in 2018; however, the thresholds remained unchanged. It should be noted that for impulsive sounds, the biologist must also consider peak sound pressure thresholds (dual thresholds). These thresholds are summarized in Table 7-29.

Table 7-28. Marine Mammal Injury and Disturbance Thresholds

<table>
<tr><th rowspan="4">Functional Hearing Group</th><th>In Air Noise Thresholds</th><th colspan="5">Underwater Noise Thresholds</th></tr>
<tr><td rowspan="2">Disturbance Threshold</td><td colspan="3">Impulsive Sound
Impact Pile Driving</td><td colspan="2">Non- Impulsive Sound
Vibratory Pile Driving</td></tr>
<tr><td colspan="2">Auditory Injury Threshold (PTS)</td><td>Behavioral Disturbance Threshold</td><td>Auditory Injury Threshold (PTS)</td><td>Behavioral Disturbance Threshold</td></tr>
<tr><td>dB RMS (unweighted)</td><td>Peak SPL</td><td>dB SEL_{cum}</td><td>dB RMS</td><td>dB SEL_{cum}</td><td>dB RMS</td></tr>
<tr><td>Low-frequency Cetaceans</td><td>NA</td><td>219</td><td>183
LF, 24h</td><td>160</td><td>199</td><td>120</td></tr>
<tr><td>Mid-frequency Cetaceans</td><td>NA</td><td>230</td><td>185
MF, 24h</td><td>160</td><td>198</td><td>120</td></tr>
<tr><td>High-frequency Cetaceans</td><td>NA</td><td>202</td><td>155
HF, 24h</td><td>160</td><td>173</td><td>120</td></tr>
<tr><td>Phocid Pinnipeds (seals)</td><td>90</td><td>218</td><td>185
PW,24 h</td><td>160</td><td>201</td><td>120</td></tr>
<tr><td>Otariid Pinnipeds (sea lions)</td><td>100</td><td>232</td><td>203
OW,24h</td><td>160</td><td>219</td><td>120</td></tr>
</table>

The equations and procedures described in Section 7.1.4.2 can be used to determine the extent of project related noise above the airborne disturbance threshold for pinnipeds. The next section presents how to determine the extent of pile installation noise over the underwater disturbance and injury thresholds for marine mammals and other species. The following section is consistent with NOAA guidance that was developed to outline how to more accurately estimate sound propagation for pile driving sounds relevant to marine mammals. This guidance is available on the web at: http://www.nmfs.noaa.gov/pr/acoustics/guidelines.htm .

It is recommended that BA authors review the NOAA or WSDOT website for the latest information regarding these changes. A summary of existing thresholds for fish and marine mammals is available on the WSDOT website: http://www.wsdot.wa.gov/environment/technical/fish-wildlife/policies-and-procedures/esa-ba/preparation-manual

7.2.4.5 Extent of Project-Related Noise and Effect Determinations

The threshold levels established above can be used to define the zone of potential impact for salmon, bull trout, marine mammals, and diving marbled murrelets. For example, the zone of impact for injury to these species would occur in the area where project-related noise has not yet attenuated below the injury threshold level. These distances can be calculated by using the Practical Spreading Loss model above, substituting the threshold level for the background level to determine the transmission loss. To facilitate these calculations, both NMFS and USFWS have developed spreadsheets for determining the extent of impacts relative to established thresholds. These spreadsheets are available on the WSDOT biology website: http://www.wsdot.wa.gov/environment/technical/fish-wildlife/policies-and-procedures/esa-ba/preparation-manual

The following example, based on information at the Seattle Ferry Terminal, uses the Practical Spreading Loss model to illustrate the procedure for determining the distance to peak, RMS, and cSEL thresholds for fish, diving marbled murrelets, and whales. It is important to note, that this example examines the effects associated with impact driving of 30-inch diameter steel piles. For many marine pile-driving consultations, multiple pile types and sizes may be installed in a single project, some by impact hammer and some by vibratory hammer, requiring the biologist to complete a separate analysis for each pile size/pile type/installation method scenario to fully understand the overall project effects on various species.

1. **Estimate the peak, RMS, and single strike SEL levels for the project.** If site specific data for the location, pile size, and pile type are available, use them as an estimate of the expected source levels of pile driving noise for the project. If not, for impact pile driving, use Table 7-14, unmitigated sound pressure levels associated with pile types (also available at http://www.wsdot.wa.gov/environment/technical/fish-wildlife/policies-and-procedures/esa-ba/preparation-manual) to estimate the source level in decibels for peak and RMS SPLs and single strike SEL for various pile diameters and types. To assure the values are agreed to by the Services, they should be presented at a pre-BA meeting.

    - ***Example** – An impact hammer will install 30-inch diameter steel piles. No site specific data on pile driving noise is available. From Table 7-14, at 10 meters, and assuming a worse-case scenario, peak noise levels are estimated at 209 dB, RMS levels at 191 dB, and an SEL (single strike) at 179 dB.*

2. **Estimate the number of strikes per summation period.** The summation period is the number of piles **struck** in a period of time (typically this is per day) until there is a rest period (usually a 12- to 18-hour period) where no strikes occur. The Pile Strike Summary Tables at http://www.wsdot.wa.gov/environment/technical/fish-wildlife/policies-and-procedures/esa-ba/preparation-manual provide data from previous projects on the number of pile strikes per day for steel and concrete piles with hammer

type energy ratings. The data in the tables can be used to calculate the cumulative SEL (SELcum). A link to the CalTrans Pile Driving Compendium is also provided for comparison. Focus on selecting data that reflects similarities to your site and project. If there is site specific data, or data from sites with similar soils, use it. Also be sure to consider hammer size.

- ***Example*** *–Using data from the first Pile Strike Summary Table, it was determined the conditions at the project site are most similar to the Anacortes ferry terminal. Therefore, the project is estimated to strike the four piles 2,494 times per day (624 strikes per pile for four piles over the time period of 1 day.*

3. **Estimate noise reduction from a bubble curtain or other noise attenuation device.** As stated previously, the use of a noise attenuation device can reduce the noise levels at the source. However, because of the large variability in the effectiveness of bubble curtains, the expected level of attenuation from these or any other noise attenuation device should be discussed with the Services prior to submitting the BA in a pre-BA meeting. Use site-specific and attenuation-device-specific data if it is available. Otherwise, select attenuation-device-specific-data and report the mean and standard deviation. If there are a wide range of attenuation values available from several projects, report the means and standard deviations from those projects. You will need to run the spreadsheet several times to capture potential scenarios and to assess an accurate range of expected sound attenuation.

   - ***Example*** *– An unconfined bubble curtain will be used during impact pile driving. Based on past experience with this design of bubble curtain, at this location, a mean of 12 dB reduction in noise levels, with a range of 0-32dB reduction and a standard deviation of 8.7, is expected at 10 meters from the source. Since some unattenuated pile driving will occur – we would calculate the extent of effects resulting from unattenuated pile driving, which would persist for a very short time period (usually 5-minutes per pile). The project biologist would also need to calculate effects, assuming the mean noise reduction or some other value, for the remaining time period when the unconfined bubble curtain would be employed. For this example, we will conservatively assume 10 dB reduction, slightly less than the mean. The project biologist might also calculate effects associated with low and high values within the documented range of attenuation values.*

4. **Determine if the fish being evaluated in the area affected by pile driving are ≥2 grams or <2 grams.** NMFS is working on tables that list the month fish in each listed ESU reach 2 grams. This table is incomplete

at this time, but may be posted at a later date on our website. Use site-specific ESU information for the area where the project is located, if available. Note that separate ESA and EFH analyses may be required. All marine and estuarine areas have fish less than 2 grams present at all times. The USFWS considers bull trout to be less than 2 grams in Washington where local populations occur in core areas (not in FMO) from December 15 to September 30 with the exception of the Puyallup core area, where bull trout may be less than 2 grams in local population areas from November 15 to August 30.

5. **Use the USFWS or NMFS Spreadsheets** (available on the WSDOT website) **or the Practical Spreading Loss model to determine the extent of the distances to the thresholds for injury and potential disturbance effects for fish, marbled murrelets, and thresholds for potential disturbance for marine mammals. Use the NMFS Acoustic Technical Guidance to determine the extent of the distances to the injury thresholds for marine mammals.** To determine the effectiveness of a noise attenuation device, some **hydroacoustic** measurements will be made without the device operating; therefore, estimates with and without the estimated reduction in SPL and SEL from a noise attenuation device must be calculated.

   In general, when calculating the extent of effects of the project to listed species, use the appropriate injury, disturbance, and behavior threshold values in your practical spreading loss calculations to calculate the distance at which sound will attenuate to threshold sound levels. For marine mammal functional hearing groups, if the background sound level is higher than the disturbance threshold number, , the background sound value should be used instead. If the threshold value is higher than background sound, it should be used. For example, in the case of vibratory driving in Edmonds, a biologist would use the 120 dB_{RMS} threshold rather than the 104 dB_{RMS} background sound level listed for high frequency cetaceans listed in Table 7-13.

   Since there is currently no vibratory threshold identified for fish or marbled murrelet, the broadband background sound will not be used to determine the extent of effects to those species, as the injury and harassment thresholds will be reached long before the sound attenuates to background.

   - **Example** – **TL = 15Log(R_1/R_2), or solved for R_1, R_1 = ($10^{(TL/15)}$)(R_2).** R_1 is the distance where noise attenuates to threshold levels, R_2 is the range of the known noise level, and TL is the amount of spreading loss (estimated noise level – threshold level). (Note: Spreadsheets for TL are available at http://www.wsdot.wa.gov/environment/technical/fish-wildlife/policies-and-procedures/esa-ba/preparation-manual . See NMFS spreadsheet and USFWS Marbled Murrelet SEL spreadsheet.)

- **Peak**

  Estimated distance to the injury (206 dB_{PEAK}) threshold for fish

  $10 * 10^{((212-206))/15)} = 25$ *meters*

  (With noise attenuation) $10 * 10^{((202-206))/15)} = 5$ *meter*

- **RMS**

  Estimated distance for potential behavioral effects (150 dB_{RMS}) for fish and diving murrelets

  $10 * 10^{((195-150)/15)} = 10{,}000$ *meters*

  (With noise attenuation) $10 * 10^{((185-150)/15)} = 2{,}154$ *meters*

  Estimated distance for potential disturbance effects (160dB_{RMS}) for marine mammals (for impulse sound)

  $10 * 10^{((195-160)/15)} = 2{,}154$ *meters*

  (With noise attenuation) $10 * 10^{((185-160)/15)} = 464$ *meters*

  Estimated distance for potential injury for cetaceans

  Use the NMFS Acoustic Technical Guidance spreadsheets to determine the extent of the distances to the injury thresholds for cetaceans. In this example using unattenuated pile driving, the humpback whale (low frequency cetacean) injury threshold distance is 2,912 meters. The killer whale (mid-frequency cetacean) injury threshold is 104 meters).

  With noise attenuation, the humpback whale injury threshold distance is 627 meters, and the killer whale injury threshold distance is 22 meters.

- **cSEL (for fish).** Calculate the injury and behavioral threshold areas, for stationary fish. The NMFS spreadsheet on the WSDOT website is for stationary fish. If you have “moving” fish (fish that will only be moving through a project area) and the Services agree, then use a specialized NMFS spreadsheet for moving fish that is available upon request. This spreadsheet is only available from NMFS.

  *cSEL = SEL(single strike at ~ 10 meters) + 10 Log * (# strikes)*

  186 + 10Log(2,494) = 220 dB

  *(With noise attenuation) 176 * 10Log(2,494) = 210 dB*

It is important to note that NMFS and USFWS assume that single strike SELs below 150 dB do not accumulate to cause injury. This concept, effective quiet (EQ), is built into the NMFS spreadsheet for assessing pile driving injury to fish from noise and into the USFWS spreadsheet for assessing pile driving injury to bull trout and marbled murrelets. So if the distances calculated to the cumulative SEL thresholds described above (183 dB_{SEL} and 187 dB_{SEL} for fish) are greater than the distance calculated to effective quiet, the spreadsheet will default to the effective quiet distance when defining the area of injury.

Estimated distance to injury threshold (**187 dB_{SEL}) **for fish ≥2 grams

$$10 * 10^{(220-187)/15)} = 1{,}584 \text{ meters}$$

$$\text{(With noise attenuation) } 10 * 10^{((210-187))/15)} = 341 \text{ meters}$$

Estimated distance to injury threshold (**183 dB_{SEL}) **for fish <2 grams

$$10 * 10^{((220-183)/15)} = 2{,}929 \text{ meters}$$

$$\text{(With noise attenuation) } 10 * 10^{((210-183))/15)} = 631 \text{ meters}$$

***Estimated distance to effective quiet** – To calculate the distance to effective quiet, the same Practical Spreading Loss equation is used, but rather than using the cumulative SEL value (220 dB) minus the threshold SEL (187 or 183 dB)/15 as the exponent, use the estimated SEL for the pile driving noise (186 dB) minus Effective Quiet (150 dB)/15 as the exponent. The correct equation is provided below for this example:*

$$10 * 10^{((186-150)/15)} = 2{,}512 \text{ meters}$$

The distance calculated to the 187 db cumulative SEL threshold calculated above is less than EQ, so the 1,577-meter distance is used to define the extent of injury for fish >2 grams. However, the distance calculated to the 183 db cumulative SEL threshold calculated above, exceeds the distance calculated to effective quiet, the so the biologist should default to the effective quiet distance (2, 512 meters) when defining the area of injury for fish <2 grams.

- **cSEL (for diving marbled murrelets).** Remember there are two different injury thresholds to evaluate for marbled murrelets: one for permanent hearing impacts (injurious auditory), and one for non-auditory injury (barotrauma). The USFWS spreadsheet may be used to determine the distances to these thresholds.

  *cSEL = SEL(single strike at ~ 10 meters) + 10 Log * (# strikes)*

  $$186 + 10Log(2{,}494) = 220 \text{ dB}$$

  $$\text{(With noise attenuation) } 176 * 10Log(2{,}494) = 210 \text{ dB}$$

It is important to note that USFWS assumes that single strike SELs below 150 dB do not accumulate to cause injury. This concept, effective quiet (EQ), is built into its spreadsheet for assessing pile driving injury to fish and diving marbled murrelets from noise. So if the distances calculated to the cumulative SEL thresholds described above are greater than the distance calculated to effective quiet, the spreadsheet will default to the effective quiet distance when defining the area of injury.

Estimated distance to injurious auditory threshold (202 dB SEL)

$$10 * 10^{((220-202)/15)} = 158 \text{ meters}$$

$$\text{(With noise attenuation) } 10 * 10^{((210-202))/15)} = 34 \text{ meters}$$

Estimated distance to non-auditory injury threshold (208 dB SEL)

$$10 * 10^{((220-208)/15)} = 63 \text{ meters}$$

$$\text{(With noise attenuation) } 10 * 10^{((210-208))/15)} = 14 \text{ meters}$$

Estimated distance to effective quiet *– To calculate the distance to effective quiet, the same Practical Spreading Loss equation is used, but rather than using the cumulative SEL value (220 dB) minus the threshold SEL /15 as the exponent, use the estimated SEL for the pile driving noise (186 dB) minus Effective Quiet (150dB)/15 as the exponent. The correct equation is provided below for this example:*

$$10 * 10^{((186-150)/15)} = 2{,}512 \text{ meters}$$

- The distance calculated to the 183 db cumulative SEL threshold calculated above, exceeds the distance calculated to effective quiet, the so the biologist should default to the effective quiet distance (2,512 meters) when defining the area of non-injurious auditory effects.

- *Therefore, according to the Practical Spreading Loss model, in open water with no noise attenuation, impact pile driving noise would be expected to attenuate to the injury threshold for fish at 25 meters for peak levels, 584 meters for cSEL levels for fish $\geq$2 grams, and 2,512 meters for fish <2 grams. For this project with 2,494 pile strikes, the most conservative metric to estimate the distance to the injury threshold for fish would be the cSEL.*

- *The distance to the injury threshold for humpback whale and killer whale is estimated to extend 2,912 meters and 104 meters, respectively, in open water without the noise attenuation.*

- *For marbled murrelets, the distance to the non-injurious auditory threshold would be 2,512 meters, 158 meters for the auditory injury threshold, and 63 meters for potential non-auditory injury (barotraumas).*

- *In open water with no noise attenuation, pile driving noise would be expected to attenuate to the disturbance threshold for marine mammals at 2.1 kilometers.*

- *These distances would be worst case for impact pile driving and would only be expected to occur when the noise attenuation device was not in operation. Therefore, also include in the BA the expected distances to the thresholds with the expected reduction from the noise attenuation device.*

  If a project would involve impact pile driving for other pile types or pile sizes, or if it would involve vibratory installation, this analysis should be repeated for each scenario as appropriate.

- ***Map the extent of the distance to each threshold, and provide figures and tables summarizing these distances.*** *As stated in the previous example, noise pressure travels in a linear direction (concentrically) away from the source; when the noise intersects a landmass, it is assumed that it does not travel through the land mass or reflect off of the land mass. Therefore, the project biologist should determine where the thresholds extend based on land masses.*

6. **Estimate the area being affected.** For the area within a mapped circular threshold, the area is calculated simply as πR^2. For irregular shaped areas, use Geographic Information System tools.

7. **If possible, estimate how many individuals are being affected.** If fish distribution, murrelet foraging, or marine mammal distribution data are available, use it to estimate the number of individuals in the affected area.

As mentioned above, the disturbance threshold should be considered the “may affect” threshold. The project effect determination for fish, for example, is not automatically a “not likely to adversely affect” merely because the noise level is above the disturbance threshold but below the injury threshold. Other project conditions, such as timing, duration, or life history information may also be necessary to ensure the effects from noise are insignificant or discountable. Likewise, behavioral disruption could also result in a likely to adversely affect situation if measures cannot be taken to minimize effects.

Even if a species is outside the zone of behavioral disruption (below 150 dB_{RMS} for salmonids and diving marbled murrelet, or below 160 dB_{RMS} for marine mammals for impulse sounds (impact pile driving) and 120 dB RMS for vibratory sound), a *no effect* determination may not be warranted. For a *no effect* determination, the species must be located in a zone where all underwater noise has attenuated to baseline levels.

It is important to realize when using the threshold levels identified above that the injury and disturbance thresholds are measured in three different metrics, dB_{peak}, dB cSEL, and dB_{RMS}. When using the models, it is crucial to compare like values to ensure accuracy. For example, a noise level measured in peak should not be used to determine the distance of the disturbance threshold, which is measured in RMS. Likewise, using an RMS noise level to identify the injury threshold (peak) will lead to incorrect results.

7.2.4.6 Anticipated Project Requirements

The Services have completed recent consultations that have developed reasonable and prudent measures requiring underwater pile driving projects to mitigate for potential impacts. The bulleted statements below summarize what anticipated requirements may be for underwater pile driving projects:

- Vibratory hammers may be required where substrate conditions allow.

- Hydroacoustic monitoring will likely be required on any project with impact pile driving. A standard plan to conduct hydroacoustic monitoring is required for WSDOT projects. A template for the standard plan is available at < http://www.wsdot.wa.gov/environment/technical/fish-wildlife/policies-and-procedures/esa-ba/preparation-manual >. The template should be filled in with project specific information and then included in the BA as an appendix. Check the webpage above for the most current version of the template.

- Visual marine mammal monitoring will likely be required for listed species that may be potentially present. For listed marine mammal species, such as the southern resident killer whale or humpback whale, shut-down of impact or vibratory pile driving must occur for the area within the behavioral threshold, unless incidental take has been granted through both an ESA Section 7 consultation and an MMPA authorization. Shut-down of pile driving will always be required if any marine mammal (listed or not listed) approaches the injury zone (see subsection below on *Determining the Area for Marbled Murrelet and Marine Mammal Monitoring Plans*).

- Visual marbled murrelet monitoring will likely be required if a project occurs where marbled murrelets may be potentially present. Shut-down of impact pile driving must occur for the area within the masking area of effect of atypical projects, unless incidental take has been granted through an ESA Section 7 consultation. Shut-down of pile driving will always be required if any marbled murrelet approaches the injury zone for the underwater threshold (see *Determining the Area for Marbled Murrelet and Marine Mammal Monitoring Plans* subsection below).

- If the use of a bubble curtain or other attenuation method is not proposed, the Services may require the use of an attenuation method if SPLs or cumulative SELs exceed the threshold limits for a certain amount of time. For example, pile driving without a bubble curtain may be allowed only if constant monitoring indicates the cumulative SEL levels do not exceed either the 183 dB or 187 dB cumulative SEL thresholds and peak levels never exceed 206 dB. If the cumulative SEL levels exceed either 183 dB or 187 dB, OR peak values exceed the 206 dB threshold, a bubble curtain will likely be required. However, these conditions are site and project specific.
- The design of any bubble curtain to be used will need to be reviewed in advance by the Services.

A monitoring report should be submitted to the Services after pile driving is completed. Required report details are determined during consultation or outlined in the standard templates available at http://www.wsdot.wa.gov/environment/technical/fish-wildlife/policies-and-procedures/esa-ba/preparation-manual >.

7.2.4.7 Determining the Area for Marbled Murrelet and Marine Mammal Monitoring Plans

To minimize or avoid impacts, resulting from elevated underwater sound, to marbled murrelets and marine mammals, visual monitoring is often required. The monitoring zones are defined according to the areas of effect that are established in the analysis of effects section. For each of the noise scenarios analyzed, a different area may be established for monitoring.

For example, if a project will be impact driving 18-inch diameter steel piles for four days and 36-inch diameter steel piles for a two-week period, different monitoring zones would be established for these four-day and two-week periods.

- The monitoring zones during the four-day period (when 18-inch piles are being driven) would be determined by using the practical spreading loss model or relevant NMFS and USFWS calculators and established thresholds or frequency-weighted background sound levels to calculate areas of effect for each of the potentially affected species. As a result, multiple areas, of different sizes would be defined to ensure adequate monitoring coverage for each of the target species. These may be consolidated to simplify monitoring.

- The monitoring zones for the two-week period (when 36-inch piles are being driven) would be determined the same way, and would likely be substantially larger due to the higher source sound levels associated with installation of larger piles.

Once these areas have been established, a monitoring plan must be developed to ensure adequate coverage of the monitoring zone. USFWS has developed a template for marbled murrelet monitoring plans that can be acquired by contacting USFWS in the Lacey, Washington office. Marine mammal monitoring plans will be developed separately.

If this project also involved impact installation of different pile types (wood, concrete, etc.) or pile sizes, areas of affect and associated monitoring areas (if the areas of effect are not insignificant) would be established for each noise scenario.

If this same project also involved vibratory installation of piles, at this time, since no vibratory thresholds have been established for marbled murrelets, no monitoring would be required for murrelets during vibratory installation. However, for marine mammals, because a 120 dB_{RMS} disturbance threshold has been established for continuous sound (vibratory hammering), areas of effect and associated monitoring areas would need to be established. As is described above, these areas are determined by using the 120 dB_{RMS} disturbance threshold OR frequency-weighted background sound levels (whichever is greater) and the practical spreading loss model, to determine the attenuation distances to the target threshold or species-specific background sound levels. In 2016, NMFS published acoustic technical guidance that includes continuous noise injury thresholds for five marine mammal functional hearing groups (although the guidance was updated in 2018, the injury thresholds remain unchanged). Using the spreadsheets available on the WSDOT or NMFS websites, the biologist would also be required to determine these additional attenuation distances. Once these distances and the affected areas have been established, a monitoring plan that provides adequate coverage of the areas for the target species must be developed.

7.3 References

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