APPENDIX K

CRC HYDROACOUSTICS TECHNICAL REPORT

June 2010

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ACRONYMS

µ	micro-; 10^{-6}
µPa	Micropascal
ADD	Acoustic Deterrent Devices
ADT	Average Daily Traffic
BA	Biological Assessment
bike/ped	Bicycle/Pedestrian
BMP	Best Management Practice
BO	Biological Opinion
BRT	NMFS Biological Review Team
C	Celsius
Caltrans	California Department of Transportation
CAO	Clark County Critical Areas Ordinances
CBR	Columbia Basin Research
CDFG	California Department of Fish and Game
cfs	Cubic Feet per Second
CPUE	(Eulachon) Catch per Unit Effort
CR	Columbia River (ESU/DPS)
CRC	Columbia River Crossing
CRD	Columbia River Datum
CREDDP	Columbia River Estuary Data Development Program
C-TRAN	Clark County Public Transit Benefit Area Authority
CWA	Clean Water Act
CY	Cubic Yard
DART	Data Analysis in Real Time
dB	Decibel
dB peak	Peak Injury Threshold (in decibels)
dB RMS	Root Mean Square of Sound Pressure Levels (measured in decibels)
DEQ	Oregon Department of Environmental Quality
DOE	U.S. Department of Energy
DOT	Department of Transportation
DPS	Distinct Population Segment
DSL	Oregon Department of State Lands

Ecology	Washington State Department of Ecology
EFH	Essential Fish Habitat
EO	Executive Order
EPA	Environmental Protection Agency
ESA	Endangered Species Act
ESC	Erosion And Spill Control
ESH	Essential Salmonid Habitat
ESU	Evolutionarily Significant Unit
F	Fahrenheit
FHWA	Federal Highway Administration
FHWG	Fisheries Hydroacoustic Working Group
FPAC	Fish Passage Advisory Committee
FPC	Fish Passage Center
fps	Feet per Second
FR	Federal Register
FTA	Federal Transit Administration
g	Gram
GIS	Geographical Information System
HIWWW	Hydroacoustic In-Water Work Window
HPA	Hydraulic Project Approval
HUC	Hydrologic Unit Code
Hz	Hertz
I-5	Interstate 5
ICTRT	Interior Columbia Technical Recovery Team
InterCEP	Interstate Collaborative Environmental Process
ISAB	Independent Scientific Advisory Board
IWWW	In-Water Work Window
JCRMS	Joint Columbia River Management Staff
JISAO	Joint Institute for the Study of Atmosphere and Ocean
km	Kilometer
LCFRB	Lower Columbia Fish Recovery Board
LCR	Lower Columbia River (ESU/DPS)
log	Logarithm
LRT	Light Rail Transit

m	Meter
m/s	Meters per Second
mm	Millimeter
MAX	Metropolitan Area Express
MCDD	Multnomah County Drainage District
MCR	Middle Columbia River (ESU/DPS)
MMPA	Marine Mammal Protection Act
MPG	Major Population Group
mph	Miles per Hour
MSA	Magnuson-Stevens Fishery Conservation and Management Act
MUP	Multi-Use Path
NAVD88	North American Vertical Datum of 1988
NFH	USFWS National Fish Hatchery
NGVD	National Geodetic Vertical Datum
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
NTU	Nephelometric Turbidity Unit
NWFSC	Northwest Fisheries Science Center
ODFW	Oregon Department of Fish and Wildlife
ODOT	Oregon Department of Transportation
OHW	Ordinary High Water
ORNHIC	Oregon Natural Heritage Information Center
OSU	Oregon State University
Pa	Pascal
Pa-s	Pascal-seconds
PBAC	Pedestrian and Bicycle Advisory Committee
PCE	Primary Constituent Element
PDX	Portland International Airport
PFMC	Pacific Fishery Management Council
PGIS	Pollution-Generating Impervious Surfaces
PIDP	San Francisco-Oakland Bay Bridge Pile Installation Demonstration Program
PIT	Passive Integrated Transponder
PTS	Permanent Threshold Shift

Q_P	Flow Rate of the Project Runoff, in cfs
Q_R	Flow Rate of the Receiving Waterbody, in cfs
r	Radius
RKm	River Kilometer
RM	River Mile
RMS	Root Mean Square
SEL	Sound Exposure Level
SEL_{cum}	Cumulative Sound Exposure Level
σ	Sigma; Standard Deviation
SMA	Shoreline Management Act
SPCC	Spill Prevention, Control, and Countermeasures
SPL	Sound Pressure Level
SPUI	Single Point Urban Interchange
sq. ft.	Square Foot/Square Feet
SR	State Route or Snake River (ESU/DPS)
TL	Transmission Loss
TNAP	Temporary Noise-Attenuation Pile
TriMet	Tri-County Metropolitan Transportation District of Oregon
TTS	Temporary Threshold Shift
UCR	Upper Columbia River (ESU/DPS)
URB	Upriver Bright (Chinook)
USACE	U.S. Army Corps of Engineers
USC	United States Code
USCG	U.S. Coast Guard
USGS	U.S. Geological Survey
USFWS	U.S. Fish and Wildlife Service
UW	University of Washington
UWR	Upper Willamette River (ESU/DPS)
WDFW	Washington Department of Fish and Wildlife
WDNR-NHP	Washington Department of Natural Resources, Natural Heritage Program
WLCTRT	Willamette/Lower Columbia Technical Recovery Team
WSDOT	Washington State Department of Transportation
WSF	Washington State Ferries

GLOSSARY

action – Any activity or program of any kind authorized, funded, or carried out, in whole or in part, by federal agencies in the United States or upon the high seas. Examples include but are not limited to actions directly or indirectly causing modifications to the land, water, or air; actions intended to conserve listed species or their habitat; and the promulgation of regulations (50 CFR 402.02).

action agency – The federal agency proposing to undertake a major construction project (action).

action area – All areas to be affected directly or indirectly by the federal action and not merely the immediate area involved in the action (50 CFR 402.02).

affect/effect – To *affect* (a verb) is to bring about a change. The *effect* (usually a noun) is the result.

ambient noise level – The background sound level, which is a composite of sound from all sources near and far.

attenuation – See *transmission loss*.

best management practices (BMPs) – Methods, facilities, built elements, and techniques implemented or installed during project construction to reduce short- and long-term project impacts on listed and sensitive species and habitat. These measures are included as part of the federal agency's proposed action.

biological assessment (BA) – The information prepared by or under the direction of an action agency to determine whether a proposed action (major construction activity) is likely to affect listed and proposed species and designated and proposed critical habitat that may be present in the project action area, including the evaluation of potential effects of the action on such species and habitat. The outcome of the BA determines whether formal consultation or a conference is necessary.

biological opinion (BO) – The document prepared by the U.S. Fish and Wildlife Service (USFWS) or National Marine Fisheries Service (NMFS) that states the opinion of the Service as to whether a federal action is likely to jeopardize the continued existence of listed species or result in the destruction or adverse modification of critical habitat.

bycatch – The unintentional harvest of a fish species while intending to catch another fish species.

candidate species – A species for which the Service has on file sufficient information on biological vulnerability and threats to support a proposal to list it as threatened or endangered.

cofferdam – An enclosure to isolate work activities from the active channel of a waterbody; it may be dewatered.

conservation measure – Activities or measures that help recover listed species.

critical habitat – Specific geographical areas that possess physical or biological features that are essential to the conservation of listed species. These designated areas may require special management consideration or protection.

cumulative effects – The effects of other, future state or private actions that are reasonably certain to occur within the federal project action area (50 CFR 402.02).

decibel (dB) – A unit describing the amplitude of sound, equal to 20 times the logarithm to the base 10 of the ratio of the pressure of the sound measured to the reference pressure. The reference pressure for water is 1 micropascal (μPa) and air is 20 micropascals (the threshold of healthy human audibility).

delayed mortality – When a fish dies more than 1 hour and less than 48 hours after exposure to an effect.

direct effects – Impacts resulting from the proposed action.

distinct population segment (DPS) – A designation usually used by the USFWS for a discrete vertebrate stock that is treated as an individual species (e.g., a specified seasonal fish run in a particular river). This is equivalent to the NMFS evolutionarily significant unit (ESU) classification.

drilled shaft – Constructed in diameters ranging from 18 inches to 12 feet or more to provide deep foundations for buildings, bridges, and retaining walls, and to stabilize landslides. Highly specialized construction techniques have been developed to install drilled shafts in conditions ranging from soft soils to hard rock.

effect/affect – See *affect/effect*.

effects of the action – The direct and indirect effects of a federal action on listed species or critical habitat, together with the effects of other interrelated and interdependent activities. Direct effects are those resulting from the proposed action. Indirect effects are those caused by the proposed action later in time, but still reasonably certain to occur. Interrelated actions are part of a larger action and depend on the larger action for their justification. Interdependent actions are those that have no independent utility apart from the action under consideration.

endangered species – A species that is in danger of extinction throughout all or a significant portion of its range.

estuary (the Columbia River) – The Columbia River estuary is considered to be that portion of the Columbia River extending from the mouth upstream to, and including, all tidally influenced areas (i.e., to Bonneville Dam).

evolutionarily significant unit (ESU) – A designation used by NOAA Fisheries for certain local salmon populations or runs that are treated as individual species. This is equivalent to the distinct population segment (DPS) classification.

federal action agency – The federal agency that proposes a specific action or triggers a federal nexus for a project (by providing permits, funding, etc.). This agency is responsible for formally submitting a biological assessment for the proposed action to the Services for review and informal or formal consultation.

federal nexus – A project with a federal nexus either has federal funding, requires federal permits, or takes place on federal lands.

formal consultation – The process between the Services and the action agency that commences with the action agency's written request for consultation under Section 7(a)(2) of the Endangered Species Act (ESA) and concludes with the Service's issuance of a biological opinion under Section 7(b)(3) of the ESA.

habitat conservation plan (HCP) – A planning document required under Section 10(a)(1)(b) of the federal ESA for non-federal entity actions with no federal nexus to conserve the ecosystems upon which listed species depend. An HCP is part of an application for incidental take for the non-federal entity.

hair cells – Cells within the inner ear of most vertebrates that contain cilliary bundles that respond to sound pressure and create the sensation of hearing.

harass – An intentional or negligent act or omission that creates the likelihood of injury to wildlife by annoying to such an extent as to significantly disrupt normal behavior patterns, which include but are not limited to breeding, feeding, and sheltering (50 CFR Part 17).

hard site conditions – Areas where there is no excess ground-effect noise attenuation, such as asphalt, concrete, hard-packed soils, and water surfaces.

harm – In the definition of *take* in the ESA. Harm is defined by the USFWS to include significant habitat modification or degradation where it actually kills or injures wildlife by significantly impairing essential behavioral patterns, including breeding, feeding, and sheltering (50 CFR 17.3). The National Marine Fisheries Service's (NMFS's) definition of harm includes significant habitat modification or degradation where it actually kills or injures fish or wildlife by significantly impairing essential behavioral patterns, including breeding, feeding, spawning, migrating, rearing, and sheltering (64 FR 60727, November 8, 1999).

hydrology – Refers to the flow of water—its volume, where it drains, and how quickly the flow rate changes in a storm.

impulse – The time integral of the peak pressure, typically described in units of pounds per square inch per millisecond (psi/msec). It recognizes that a short pulse may do less damage than a longer duration pulse of the same pressure. Sound pressure is equivalent to kilowatts, while impulse is equivalent to kilowatt-hours.

incidental take – A *take* of listed species that results from an action but is not the direct purpose or intent of the action, as defined under the ESA. Incidental *take* can be authorized through Section 7 consultation or through Section 10 conservation planning, such as an HCP.

indirect effects – Effects caused by the proposed action later in time but still reasonably certain to occur.

is not likely to adversely affect – The appropriate finding in a biological assessment (or conclusion during informal consultation) when effects on listed species are expected to be discountable, insignificant, or completely beneficial.

jeopardize the continued existence of – To engage in an action that reasonably would be expected to directly or indirectly reduce the likelihood of both survival and recovery of a listed species in the wild by reducing the reproduction, numbers, or distribution of that species.

light rail transit (LRT) – A form of urban rail public transportation that generally has a lower capacity and lower speed than heavy rail and metro systems, but higher capacity and higher speed than traditional street-running tram systems.

listed species – Any species of wildlife, fish, or plant that has been listed as endangered or threatened under Section 4 of the ESA. Listed species are found in 50 CFR 17.11–17.12. Under the statute, the two types of species are treated in virtually the same way.

metapopulation – A metapopulation consists of a group of spatially separated populations of the same species that interact at some level. A metapopulation is generally considered to consist of several subpopulations together; each subpopulation may be separated by areas of suitable habitat that are currently unoccupied.

micropascal (µPa) – Most underwater acoustic sound pressure measurements are stated in terms of a pressure relative to 1 micropascal. One micropascal is equal one millionth of one newton per square meter.

minimization measure – Measures that reduce the impact of the project on listed species.

mode split – The percentage of travel by different forms of transportation, typically single-occupant vehicles, high-occupancy vehicles (two or more persons in a car), transit, walk, and bicycle.

mortality (fish) – Cessation of all activity including movements of the operculum, or when all respiration stops and the fish lies motionless.

National Pollutant Discharge Elimination System (NPDES) – The provision in the federal Clean Water Act that requires point source dischargers of pollutants to obtain permits, called NPDES permits. In Washington, NPDES permits are administered by the Washington Department of Ecology.

no effect – The appropriate conclusion when the proposed action will not affect a listed species or its critical habitat (i.e., will have no effect whatsoever—neither beneficial effects, nor highly improbable effects, nor insignificant effects).

pascal (Pa) – A unit of pressure equal to 1 newton per square meter.

performance measure – An observable or measurable benchmark for a particular performance objective against which a project can be compared. If the standards are met, the related performance objectives are considered to have been fully achieved. It is something quantifiable. Standards should be measures, not actions, and should be: 1) achievable, and 2) capable of being monitored.

piles – Steel, concrete, wood, or plastic cylinders or columns that may be hammered, vibrated, or drilled into the soil until they reach dense soil or bedrock. Load-bearing piles provide support to hold the weight of a structure and any traffic and equipment. Non-load-bearing piles may be used for mooring or support.

pool – A deep, slow moving area with smooth water surface.

predation – The act of preying on another animal.

proposed species – Any species of wildlife, fish, or plant that is proposed in the Federal Register to be listed under Section 4 of the ESA as threatened or endangered.

range (of a species) – The area or region over which an organism occurs.

rate – Percentage probability of an effect.

recovery – Action that is necessary to reduce or resolve the threats that caused a species to be listed as threatened or endangered.

riffle – A shallow, fast-moving stream section with water broken by rocks and boulders.

root mean square (RMS) – The average of the squared pressures over the time that comprise that portion of the waveform containing 90 percent of the sound energy for one pile-driving impulse, commonly used in repetitive or relatively continuous measurements such as in speech or highway noise. It is not applicable to transient signals such as explosions. It is used in calculating longer-duration sound pulses such as a pile-driving pulse of sound.

Services – An abbreviated term for the USFWS and NOAA Fisheries.

sound exposure level (SEL) – A common unit of sound energy used in airborne acoustics to describe short-duration events. The time integral of frequency-weighted squared instantaneous sound pressures. It is proportionally equivalent to the time integral of the pressure squared and can be described in terms of $\mu\ Pa^2/sec$ over the duration of the impulse. Source: Fisheries and Hydroacoustic Monitoring Program Compliance Report, San Francisco-Oakland Bay Bridge East Span Seismic Safety Project 6-11.

sound pressure level (SPL) – Sound pressure is the sound force per unit area, usually expressed in micropascals (μPa) (or 20 micro newtons per square meter), where 1 pascal is the pressure resulting from a force of 1 newton exerted over an area of 1 square meter. SPL is expressed in decibels as 20 times the logarithm to the base 10 of the ratio between the pressure exerted by the sound to a reference sound pressure (e.g., 20 μPa).

species – Includes any subspecies of fish, wildlife, or plant, or any distinct population segment of any species of vertebrate fish or wildlife, which interbreeds when mature.

spherical spreading – Spreading of sound pressure in a dome or sphere shape from the source.

suitable habitat – The area where an organism, including a plant, animal, or fish, naturally or normally lives and grows.

strike interval – The length of time between strikes during pile driving.

take (taking) – Defined under the ESA 16 USC 1532(19) as to harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect, or to attempt to engage in any such conduct.

transmission loss – The accumulated decrease in acoustic intensity as the acoustic pressure wave propagates outward from the source due to spreading.

1. Introduction

1.1 Project Overview and Report Intent

The Columbia River Crossing (CRC) project is a large multimodal transportation project that proposes to replace the existing Interstate 5 (I-5) crossing over the Columbia River with new structures; extend light rail from Portland, Oregon to Vancouver, Washington; enhance pedestrian and bicycle (bike/ped) paths; and improve closely spaced interchanges. In-water pile driving will be required for the construction of bridges over the mainstem Columbia River and its side channel, the North Portland Harbor. Pile driving in other project area waters will not be required.

The CRC project area contains 15 runs of salmon and steelhead, green sturgeon, eulachon, and bull trout that are listed as federally threatened or endangered under the Endangered Species Act (ESA). However, both green sturgeon and bull trout occur in the project area in such low abundance that determining impacts to runs or populations from in-water noise cannot be achieved. The geographic distributions of the remaining fish runs extend from the upper reaches of the Columbia and Snake River systems into the Pacific Ocean. Figure 1-1 shows the range of the fish species within the Columbia River basin discussed in this report in relation to recovery domain, dams, and rivers. Distribution maps are located in Section 4 of the CRC Biological Assessment (BA).

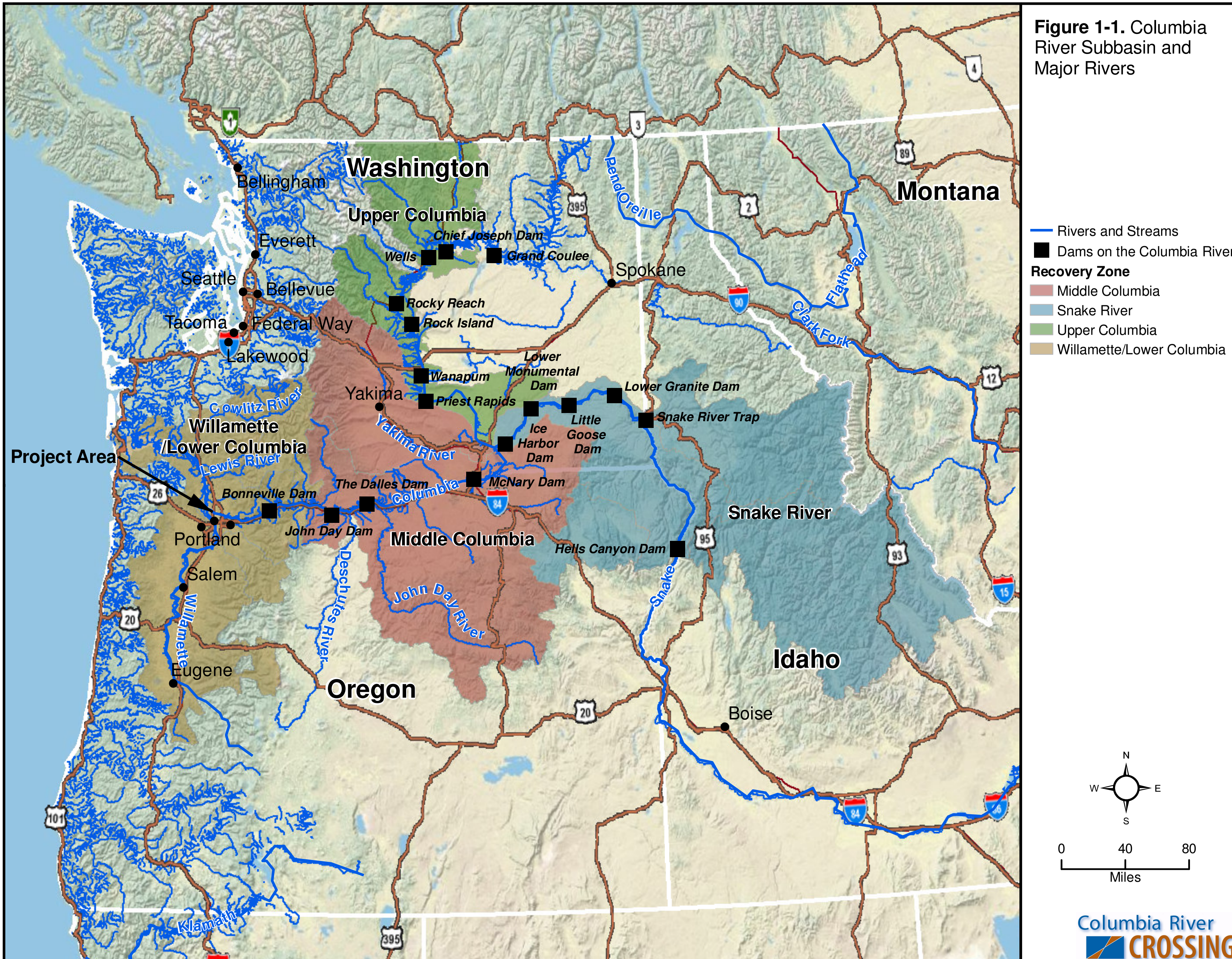
Project construction will require the installation of approximately 1,500 temporary steel piles in the Columbia River and North Portland Harbor, near river kilometer (RKm) 171 (Section 1.2). Temporary piles that must be load bearing will be vibrated to refusal, then driven and proofed with an impact hammer to confirm load-bearing capacity. Impact pile driving causes disturbance or injury to fish when it produces sound above certain levels. Therefore, potential project impacts from pile driving are of particular concern to the National Marine Fisheries Service (NMFS) and U.S. Fish and Wildlife Service (USFWS), who have regulatory oversight over the fish analyzed in this report. These impacts are also of concern to the Oregon Department of Fish and Wildlife (ODFW) and Washington Department of Fish and Wildlife (WDFW), who will issue recommendations or permits for the timing of in-water work.

The purpose of this document is to quantify the effects of pile driving on listed fish species and designated critical habitat and to minimize harm when feasible within the CRC action area.

The document begins with an overview of the fundamentals of underwater sound propagation, information about typical sound levels generated by in-water pile driving, the effectiveness of noise attenuation devices, and the effects of pile-driving noise on fish (Section 2). Sections 3 through 5 describe the methods used to quantify effects to listed fish:

1. The area of effect (Section 3).
2. The percent of the run present by week of year (Section 4).
3. The results of this analysis to each fish population and life history stage (Section 5).

Figure 1-1. Columbia River Subbasin and Major Rivers



Columbia River CROSSING

Analysis by J. Koloszar; Analysis Date: Feb. 11, 2010: File Name: ColumbiaRiverBasin.mxd

1.2 Pile Driving Description

The CRC project is a multimodal, multi-element project. The intent of this report is to provide information and analysis of hydroacoustic impacts. Presented below is information related specifically to the CRC project's proposed design and construction techniques for installation of piles in the Columbia River and North Portland Harbor. Detailed information and graphics are presented in the project description in the CRC BA.

1.2.1 Columbia River Bridges

The project will construct two new bridges across the Columbia River downstream (to the west) of the existing interstate bridges. Each of the structures will range from approximately 91 to 136 feet wide, with a gap of approximately 15 feet between them. The over-water length of each new mainstem bridge will be approximately 2,700 feet (Table 1-1).

Table 1-1. Columbia River Bridges Over-Water Dimensions

Bridge	Approximate Length Over Water	Approximate Width
I-5 Northbound	2,700 feet	Varies: 91 to 130 feet
I-5 Southbound (with LRT)	2,650 feet	Varies: 91 to 136 feet

1.2.1.1 Columbia River Bridge Design

The proposed Columbia River mainstem crossing design uses dual stacked bridge structures. The western structure will carry southbound I-5 traffic on the top deck, with LRT on the lower deck. The eastern structure will carry northbound I-5 traffic on the top deck, with bike/ped traffic on the lower deck.

The Columbia River bridges will consist of six in-water pier complexes of two piers each, for a total of 12 in-water piers. Each pier will consist of up to nine, 10-foot-diameter drilled shafts topped by a shaft cap. In-water pier complexes are labeled pier complex 2 through pier complex 7, beginning on the Oregon side. Pier complex 1 is on land in Oregon and pier complex 8 is on land in Washington. Portions of pier complex 7 occur in shallow water (less than 20 feet deep). Piers are designed to withstand the design scour without armor-type scour protection (e.g., riprap).

At each pier complex, sequencing will occur as listed below. Details of each activity are presented in the following sections:

- Install temporary cofferdam (applies to pier complexes 2 and 7 only).
- Install temporary piles to moor barges and to support temporary work platforms (at pier complex 3 through 6) and work bridges (at pier complex 2 and 7).
- Install drilled shafts for each pier complex.
- Remove work platform or work bridge and associated piles.
- Install shaft caps at the water level.
- Remove cofferdam (applies to pier complexes 2 and 7 only).

- Erect tower crane.
- Construct columns on the shaft caps.
- Build bridge superstructure spanning the columns.
- Remove tower crane.
- Connect superstructure spans with mid-span closures.
- Remove barge moorings.

1.2.1.2 Columbia River Bridge Construction Sequencing

A construction sequence was developed for building the new Columbia River bridges and demolishing the existing structures. The sequence was developed to prove constructibility of the proposed design and is a viable sequence for construction of the river bridges. Once a construction contract is awarded, the contractor may sequence the construction in a way that may not conform exactly to the proposed schedule but that best utilizes the materials, equipment, and personnel available to perform the work. However, the amount of in-water work that can be conducted at any one time is limited, and is based on three factors:

1. The amount of equipment available to build the project will likely be limited. Based on equipment availability, the CRC engineering team estimated that only two drilled shaft operations could occur at any time.
2. The physical space the equipment requires at each pier will be substantial. The estimated sizes of the work platforms/bridges and associated barges are shown in Appendix A. (This is a conceptual design developed by the CRC project team to provide a maximum area of impact. The actual work platforms will be designed by the contractor; therefore, actual sizes will be determined at a later date). The overlap of work platforms/bridges and barge space limits the amount and type of equipment that can operate at a pier complex at one time.
3. The USCG has required that one navigation channel be open at all times during construction, to the extent feasible.

1.2.1.3 Columbia River Bridge Construction Timeline

Construction is currently estimated to occur between late 2012 and 2017.

Temporary In-Water Work Structures

The project will include numerous temporary in-water structures to support equipment during the course of construction. These structures will include work platforms, work bridges, and tower cranes. They will be designed by the contractor after a contract is awarded, but prior to construction.

Work platforms will be constructed at pier complexes 3 through 6. Work platforms are each estimated to be approximately 18,225 sq. ft. in area and will surround the future location of each shaft cap. Work bridges will be installed at pier complexes 2 and 7 so that equipment can access these pier complexes directly from land. Temporary work bridges will be placed only on the landward side of these pier complexes. The bottom of the temporary work platforms and bridges will be a few feet above the water surface. The decks of the temporary work structures will be constructed of large, untreated wood beams to accommodate large equipment, such as 250-ton cranes. After drilled shafts and shaft caps have been constructed, the temporary work platforms and their support piles will be removed.

After work platforms/bridges are removed at a given pier complex, one tower crane will be constructed between each pair of adjacent piers that makes up the pier complex. The crane will be used to construct the bridge columns and the superstructure. Following construction of the columns and superstructure, the tower cranes and their support piles will be removed.

Both battered and vertical steel pipe piles will be used to support the structures. In addition, four temporary piles could surround each of the drilled shafts (see Appendix A, Figure 11). Due to the heavy equipment and stresses placed on the support structures, all of these temporary piles will need to be load bearing. Load-bearing piles will be installed using a vibratory hammer and then proofed with an impact hammer to ensure that they meet project specifications demonstrating load-bearing capacity. The number and size of temporary piles for these structures is listed in Table 1-2.

Table 1-2. Summary of Steel Pipe Piles Required for Temporary Overwater Structures During Construction of Columbia River Bridges

Type of Structure	Structures	Pile Diameter (inches)	Pile Length (feet)	Average Piles per Structures	Total Piles
Work Platforms/Bridges	6	18–24	70–90	100	600
		42–48	120	32	192
Tower Cranes	6	42–48	120	8	48
Barge Moorings	N/A	18–24	70–90	Varies	80
Total	**12**	**---**	**---**	**---**	**920**

Not all of these structures will be in place at the same time. It is estimated that only 120 to 400 steel piles will be in the water at any one time.

1.2.2 North Portland Harbor Bridge

The existing North Portland Harbor bridge will be upgraded to meet current seismic standards and widened to accommodate an additional southbound I-5 on-ramp. The seismic retrofit activities will consist solely of minor modifications to the bent caps and girders that will not require in-water work. Widening of the existing structure will require, adding additional shafts adjacent to the existing bridge bents to support the additional structure width. In addition, three new bridges will be constructed across North Portland Harbor. Starting from the east, these structures will carry a collector-distributor (CD) ramp for northbound I-5, a CD ramp for southbound I-5, and LRT combined with a bike/ped path.

Each bridge will have four to five in-water bents, consisting of one to three 10-foot-diameter drilled shafts. Unlike the Columbia River piers, shafts will not be topped by a shaft cap. Current designs place all of the bents in shallow water (less than 20 feet deep). Bents are designed to withstand the design scour without armor-type scour protection (e.g., riprap).

1.2.2.1 North Portland Harbor Bridge Construction Sequencing

Construction is expected to be sequential, beginning with either of the most nearshore bents of a given bridge and proceeding to the adjacent bent. The actual sequencing will be determined by the contractor once a construction contract is awarded. No more than two of the four bridges are likely to have in-water work occurring simultaneously.

For the bents closest to shore, construction will occur from work bridges. At the other in-water bents, construction will likely occur from barges and oscillator support platforms. Oscillator support platforms are used to support the equipment used to install the steel casings for drilled shafts. This document uses the term "oscillator support platform" as a generic term; in fact, the platform may support equipment used for vibratory, rotator, or oscillator installation of steel casings.

General construction activities to build the bents and superstructure are similar to those for the Columbia River bridges, except that shaft caps will not be used and bridge decks will be placed on girders instead of balanced cantilevers.

General sequencing of the construction of a single bridge is as follows.

- Construct oscillator support platforms and work bridges using vibratory and impact pile drivers.
- Vibrate temporary piles to moor barges.
- Extract large pieces of debris as needed to allow casings to advance.
- Advance casings by one of three methods: vibrating, rotating, or oscillating.
- Drill shafts inside of casings.
- Construct columns on the drilled shafts.
- Construct a bent cap or crossbeam on top of the columns at a bent location.
- Erect bridge girders on the bent caps or crossbeams.
- Place the bridge deck on the girders.
- Remove temporary work bridges, oscillator support platforms, and supporting piles.

Some of these activities will occur simultaneously at separate bents.

1.2.2.2 North Portland Harbor Bridge Construction Timeline

Construction is currently estimated to occur between 2013 and 2020.

1.2.2.3 Temporary In-Water Work Structures

At the eight bents closest to shore, nine temporary work bridges will be constructed to support equipment for drilled shafts. In addition, at each of the 31 bent locations, one oscillator support platform will be constructed, each consisting of four load-bearing piles. The bridges and oscillator support platforms will be designed by the contractor after a contract is awarded, but prior to construction. The bottom of the temporary work structures will be between 0 and 5 feet above the water line. Due to the heavy equipment and stresses placed on these structures, the supporting piles will need to be load bearing. All will be installed first with a vibratory hammer and then proofed with an impact hammer to ensure that they meet specifications for load-bearing capacity. The number and size of piles for temporary in-water work structures are listed in Table 1-3.

Table 1-3. Approximate Number of Steel Pipe Piles Required for Temporary Overwater Structures for Construction of North Portland Harbor Bridges

Type of Structure	Structures	Pile Diameter (inches)	Pile Length (feet)	Average Piles per Structures	Total Piles
Work Bridges	9	18–24	70–120	25	225
Oscillator Support Platforms	31	36–48	120	4	124
Barge Moorings	N/A	36–48	120	N/A	216
Total	**40**	**18–24**	**70–120**	**29**	**565**

Following installation of the drilled shafts, the temporary work structures and their support piles will be removed through vibratory methods.

2. Sound and Its Effects on Fish

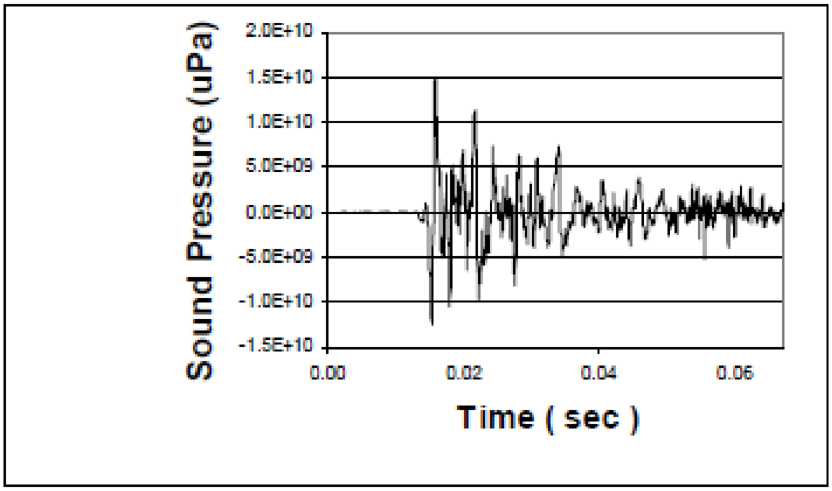
This section discusses the fundamentals of underwater sound, techniques for measurement, review of literature on underwater sound, review of sound levels during pile driving, attenuation of sound, and general effects of impact and vibratory pile diving on fish. Caltrans (2009) has defined "sound" as "small disturbances in a fluid from ambient conditions through which energy is transferred away from a source by progressive fluctuations of pressure (or sound waves)." Noise is often characterized as unwanted sound. The terms sound and noise are often used interchangeably (WSDOT 2009).

Sound is a common natural phenomenon; however, measuring actual sound levels and their effects on animals presents complex issues. Noise from project activities can adversely affect fish species. This section provides an overview of how sound propagates through water, introduces some of the metrics used to measure sound, introduces models used to estimate the extent of underwater sound, discusses current thresholds and guidance used to assess the impacts of noise generated by impact pile driving on fish, and provides a literature review of the effects of sound on fish. The discussion focuses on noise generated by impact and vibratory pile driving, as these are the sources of the highest levels of project-generated noise in the action area.

2.1 Fundamentals of Underwater Sound Propagation

Sound propagates as a wave of pressure over time and space. Sound levels are expressed in decibels (dB). In a single location, sound measured and graphed as a waveform, can depict the amount of sound pressure over time (Figure 2-1). The sound wave is a fluctuation of higher pressure (or overpressure) with lower pressure (or underpressure). All sound measurements are compared to a given reference level. All underwater sound levels presented in this report are referenced to 1 microPascal (μPa)[1] when referring to sound pressure levels (SPLs) or 1 μPa^2-second when referring to sound exposure levels (SELs).

[1] The pascal (Pa) is a measure of pressure or stress, and is defined as 1 Pa = 1 newton per square meter (N/m^2). The newton, a measure of force, is approximately equal to the force of gravity exerted on an object of 0.1 kilogram (kg). It has been stated to approximate the force of gravity exerted on one small apple. One μPa = 1 Pa x 10^{-6}.



Source: WSDOT 2008.

Figure 2-1. Generalized Depiction of an Air Hammer Noise Waveform Generated by a Single Pile Strike

Several metrics are relevant to assessing impacts to listed species. A peak sound level is a measure of the maximum overpressure or underpressure created by the impact of a single event (Hastings and Popper 2005), such as an impact pile strike. It is graphed as the maximum amplitude of the wave. Figure 2-1 depicts a typical waveform, illustrating the concept of peak sound levels using the waveform generated by a single impact driving pile strike as an example. In this example, the peak sound pressure is approximately $+1.5 \times 10^{10}$ μPa.

The root-mean-square (RMS) is the quadratic mean sound pressure over the duration of an impulse. RMS is calculated by squaring all of the sound amplitudes, averaging the squares, and then taking the square root of the average (Urick 1975). RMS accounts for both positive and negative values; squaring the pressures makes all values positive so that they may be accounted for in the summation of pressure levels (Hastings and Popper 2005).

SEL is the time-integrated sound pressure squared and is a measure of the total accumulated exposure to sound over a specified period, usually one second. SEL is also known as the sound dosage. Cumulative SEL (SEL_{cum}) is a measure of the total exposure to sound over an entire period in which the noise is occurring. It is a factor of the SEL value of a single sound event (such as a single pile strike) and the number of sound events (for example, the number of pile strikes):

$$SEL_{cum} = \text{single-strike SEL} + 10 \times \log(\text{\# of pile strikes})$$

Where “log” is the base 10-logarithm function.

Rise time is the amount of time it takes for a sound impulse to rise from 10 to 90 percent of its highest or lowest value (Caltrans 2009). In general, a rapid rise time may be more injurious to aquatic animals when coupled with high sound levels (WSDOT 2008).

For consistency, the standard distance for measuring source levels of in-water sound is approximately 10 meters (m).

Transmission loss refers to the decrease in sound energy with distance from the source. Sound levels will naturally decrease as a fixed amount of sound energy is transmitted throughout a larger and larger volume of water. Sound energy does not decrease at a fixed rate over distance from the source. Rather, it dissipates geometrically, with a more rapid attenuation rate nearer the source and a slower attenuation rate further from the source. Generally, sound will attenuate by a fixed number of decibels with each doubling of distance from the source.

Transmission loss is affected by the physical characteristics of a water body. The water surface and underlying substrate may reflect sound waves (Caltrans 2009). In water less than 200 m[2] deep, this reflection may combine with the primary sound source, thereby enhancing propagation (WSDOT 2008). Other conditions such as shallow water, undulating bottom topography, and soft substrates tend to absorb sound energy, resulting in high levels of sound attenuation. In water less than 0.4 m deep, sound propagates very poorly, and most pile driving noise originating in-water above the substrate may completely attenuate at these depths (Urick 1975). However, pile-driving noise may propagate into the water column through the substrate. This phenomenon, known as sound flanking, can result in higher sound energy levels farther from the source than in areas close to the source (Caltrans 2009).Sound in hard substrates (such as clay and rock) tends to propagate sound better than soft substrates. Other environmental site conditions influence underwater sound propagation. Landforms located in or adjacent to the water (such as islands, point bars, jetties, river bends, or streambanks) may create sound "shadow" areas that are not subject to elevated sound levels because of their sheltering effect.

Water current may also influence sound propagation over long distances. Underwater sound waves tend to bend towards the water surface while moving upstream and towards the bottom while moving downstream (WSDOT 2008). Several factors increase sound propagation in water. These include increase in salinity, pressure (depth), and temperature. Sound propagation differences in saltwater versus freshwater are negligible at the distances used in this report [3] (DOSITS 2010, Laughlin 2010 personal communication).

2.2 Underwater Sound Criteria

In June 2008, the Fish Hydroacoustics Working Group[4] (FHWG) developed an agreement between the National Marine Fisheries Service (NMFS), USFWS, Oregon Department of Transportation (ODOT), California Department of Transportation (Caltrans), Washington State

[2] Within this document, measurements specific to CRC design are generally denoted in English units, e.g., 24-inch piles; other measurements are denoted in metric units (e.g., 200-m threshold diameter), as calculations for attenuation are conducted in metric units.

3 The speed of sound in water is approximately 1,500 m/s. The approximate change in the speed of sound with a change in each property is: Temperature 1°C = 4.0 meters per second (m/s); Salinity 1PSU = 1.4 m/s; Depth (pressure) 1km = 17 m/s.

[4] The Fisheries Hydroacoustic Working Group (FHWG) is composed of representatives from Caltrans, ODOT, Washington Department of Transportation (WSDOT), FHWA, NMFS Southwest and Northwest Regions, USFWS, California Department of Fish and Game (CDFG), and U.S. Army Corps of Engineers (USACE). It was established to improve and coordinate information on fishery impacts due to underwater sound pressure caused by in-water pile driving. The FHWG is supported by a panel of hydroacoustic and fisheries experts who have been recommended by the FHWG members. A steering committee oversees the FHWG and is composed of managers with decision-making authority from each of the member organizations. The goal of the FHWG is to reach agreement on: 1) the nature and extent of knowledge about the current scientific basis for underwater sound effects on fish, 2) interim guidelines for project assessment, mitigation, and monitoring for effects of pile-driving sound on fish species, and; 3) future scientific research needed to satisfactorily resolve uncertainties regarding hydroacoustic impacts on fish species.

Department of Transportation (WSDOT), and FHWA regarding interim criteria for injury to fish during noise-producing activities. The resulting criteria are: 206 dB peak, 187 dB accumulated SEL for fish greater than 2 grams, and 183 accumulated dB SEL for fish less than 2 grams (Table 2-1) (FHWG 2008). These are the currently accepted criteria for the signatories as of the date of this report. The Federal Transit Administration (FTA) was not a signatory to this agreement.

Table 2-1. Interim Sound Criteria for the Onset of Injury and Disturbance to Fish

Underwater Sound Criteria		
Size Class	**Onset of Injury Threshold**	**Behavioral Guidance**
Fish ≥ 2 grams	206 dB peak; 187 SEL_{cum}	150 dB RMS
Fish < 2 grams	206 dB peak; 183 SEL_{cum}	150 dB RMS

Note: *Where cumulative SEL is calculated as: SEL_{cum} = SEL (single strike at ~10 m from the pile) + 10 x log (# of pile strikes).

NMFS uses an SPL of 150 dB RMS as guidance for when behavioral effects can be expected. Whether these effects result in actual injury is dependent on a variety of project-specific factors. Observations from past pile driving projects have shown that migrating adult salmon do not alter their behavior when exposed to pile driving noise (Stadler 2010 personal communication).

2.3 Models for Calculating Sound Levels

Several models estimate the extent of underwater sound generated by in-water pile driving. The objective of using such models is to estimate the distances and areas within which noise is likely to exceed the threshold levels shown in (Table 2-1). These are the currently accepted criteria for the signatories as of the date of this report. The Federal Transit Administration (FTA) was not a signatory to this agreement.

In the absence of site-specific data, NMFS and USFWS accept the Practical Spreading Loss model for determining the extent of sound from a source (Davidson 2004; Thomsen et al. 2006; Stadler 2010 personal communication). The model assumes a logarithmic coefficient of 15, which equates to sound energy decreasing by 4.5 dB with each doubling of distance from the source. To calculate the loss of sound energy from one distance to another, the following formula is used:

$$\text{Transmission Loss (dB)} = 15\log(\text{Distance 1} / \text{Distance 0})$$

Distance 1 is the distance from the pile for which sound levels are calculated, and Distance 0 is the distance from the pile for which there is a known decibel level (typically 10 m from the pile). This model also solves for the distance at which sound attenuates to various decibel levels (e.g., a threshold or background level). The following equation solves for distance:

$$\text{Distance 1} = \text{Distance 0} \times 10^{(TL/15)}$$

Where TL stands for transmission loss (the difference in decibel levels between Distance 0 and Distance 1.

For example, using the distance to an injury threshold (Distance 1), the area of effect is calculated as the area of a circle, πr^2, where r (radius) is the distance to the threshold or background. If a landform or other shadowing element interrupts the spread of sound within the threshold distance, then the area of effect truncates at the location of the shadowing element.

NMFS has developed calculators for modeling the hydroacoustic area of effect for both stationary and moving fish. Data inputs include the number of pile strikes, single-strike SEL, peak SPLs, and RMS SPLs to calculate Distance 1 for each of the sound thresholds or guidance values. The moving fish model also solves for these distances, but requires specific data on fish movement rates. These data are generally lacking; but in instances where fish are known to be moving through the area at a measurable rate, the moving fish model can be applied. This model includes the same variables as those in the stationary fish model, as well as strike interval, swim speed, and the closest distance the fish passes to a pile. The moving fish model assumes a straight line of travel at constant speed. Single-strike sound levels of 150 dB SEL or below do not accumulate in either model; therefore, this value is considered “effective quiet” (Caltrans 2009).

2.4 Pile-Driving Noise

The CRC project will produce underwater noise through installation of piles for temporary in-water work platforms and temporary barge moorings. Piles will be installed by using impact and/or vibratory hammers, or by press-in techniques that do not produce notable underwater noise.

2.4.1 Impact Hammers

Several types of impact hammers are commonly used to install in-water piles: air-driven, steam-driven, diesel-driven, and hydraulic. Impact hammers operate by repeatedly dropping a heavy piston onto a pile to drive the pile into the substrate. Noise generated by impact hammers is characterized by rapid rise times and high peak levels, a combination that may be injurious to fish (Hastings and Popper 2005). Table 2-2 summarizes observed underwater noise levels generated by driving various types and sizes of piles. SPLs and SELs generated by impact pile driving are highly variable, based on site-specific conditions such as substrate, water depth, and current. Sound levels may also vary based on the size of the pile, the type of pile, and the energy of the hammer.

Table 2-2. Observed Underwater Noise Levels Generated by Impact Pile Driving

Type/Size of Pile	dB Peak	dB RMS	dB SEL
Wood piles	180	170	160
Concrete piles	192	176	174
Steel H-piles	190	175	155
12-inch steel pile	208	191	175
14-inch steel pile	195[a]	180[a]	--
16-inch steel pile	200[b]	187[b]	--
24-inch steel pile	212	189	181
30-inch steel pile	212	195	186
36-inch steel pile	214	201	186

Type/Size of Pile	dB Peak	dB RMS	dB SEL
60-inch steel pile	210	195	185
66-inch steel pile	210	195	--
96-inch steel pile	220	205	195
126-inch steel pile	213[c]	202[c]	--
150-inch steel pile	200[d]	185[d]	--

Source: Final technical guidance for assessment and mitigation of the hydroacoustic effects of pile driving on fish (Caltrans 2009).
Note: Noise levels measured at a distance of 10 m except where otherwise indicated.
a At 30 m.
b At 9 m.
c At 11 m.
d At 100 m.

2.4.2 Vibratory Hammers

Vibratory hammers install pile by vibrating them and allowing the weight of the hammer to push them into the sediment. Vibratory hammers produce much less noise than impact hammers. Peak SPLs may be 180 dB or greater, but are generally 10 to 20 dB lower than SPLs generated during impact pile driving of the same-sized pile (Caltrans 2009). Rise time is slower, reducing the probability and severity of injury to fish (USFWS 2009), and sound energy is distributed over a greater amount of time, resulting in fewer injuries to fish (Nedwell and Edwards 2002; Carlson et al. 2001).

Vibratory hammers cannot be used in all circumstances. In some substrates, the capacity of a vibratory hammer may be insufficient to drive the pile to load-bearing capacity or depth (Caltrans 2009). Additionally, some vibrated piles must also be “proofed” (that is, struck with an impact hammer) for several seconds to several minutes in order to verify the load-bearing capacity of the pile) (WSDOT 2008).

Table 2-3 outlines typical noise levels produced by installation of various types of pile using a vibratory pile driver. Note that peak sound levels range from 165 to 195 dB, whereas peak sound levels generated by impact pile driving ranges from 190 to 214 dB (Table 2-2).

Table 2-3. Summary of Unattenuated Underwater Sound Levels for Vibratory Pile Driving at 10 m from the Source

Pile Type and Approximate Size	Water Depth	Average Sound Levels (dB)		
		Peak	RMS[a]	SEL[b]
12-inch steel H-type	<5 m	165	150	150
12-inch steel pipe pile	<5 m	171	155	155
36-inch steel pipe pile – typical	~5 m	180	170	170
24-inch AZ steel sheet – typical	~15 m	175	160	160
24-inch AZ steel sheet – loudest	~15 m	182	165	165
36-inch steel pipe pile – loudest	~5 m	185	175	175
72-inch steel pipe pile – typical	~5 m	183	170	170
72-inch steel pipe pile – loudest	~5 m	195	180	180

Source: Caltrans 2009, Appendix I.
a Impulse level (35-millisecond average).
b Sound exposure level (SEL) for 1 second of continuous driving.

2.5 Noise Attenuation Devices

Noise levels can be greatly reduced during impact pile driving using noise attenuation devices. There are several types of noise attenuation devices including bubble curtains, cofferdams, and isolation casings. Three types of attenuation devices are described below.

2.5.1 Types of Noise Attenuation Devices

2.5.1.1 Bubble Curtains

Bubble curtains create a column of air bubbles rising around a pile from the substrate to the water surface. The air bubbles absorb and scatter sound waves emanating from the pile, thereby reducing the sound energy. Bubble curtains may be confined or unconfined. An unconfined bubble curtain may consist of a ring seated on the substrate and emitting air bubbles from the bottom. An unconfined bubble curtain may also consist of a stacked system, that is, a series of multiple rings placed at the bottom and at various elevations around the pile. Stacked systems may be more effective than non-stacked systems in areas with high current and deep water (Caltrans 2009).

A confined bubble curtain contains the air bubbles within a flexible or rigid sleeve made from plastic, cloth, or pipe. Confined bubble curtains generally offer higher attenuation levels than unconfined curtains because they may physically block sound waves and they prevent air bubbles from migrating away from the pile. For this reason, the confined bubble curtain is commonly used in areas with high current velocity (Caltrans 2009). In Oregon, confined bubble curtains are typically required where current velocity is 0.6 m/s or greater (NMFS 2008a).

2.5.1.2 Cofferdams

Cofferdams are often used during construction for isolating the in-water work area, but may also be used as a noise attenuation device. Dewatered cofferdams may provide the highest levels of noise reduction of any attenuation device; however, they do not eliminate underwater noise because noise can be transmitted through the substrate (Caltrans 2009). Cofferdams that are not dewatered provide very limited reduction in noise levels.

2.5.1.3 Isolation Casings

An isolation casing is a hollow pipe that surrounds the pile, isolating it from the in-water work area. The casing is dewatered before pile driving. This device provides levels of noise attenuation similar to that of bubble curtains; however, attenuation rates are not as great as those achieved by cofferdams because the dewatered area between the pile and the water column is generally much smaller (Caltrans 2009).

2.5.2 Factors Influencing Effectiveness of Noise Attenuation Devices

Both environmental conditions and the characteristics of the noise attenuation device may influence the effectiveness of the device. According to Caltrans (2009):

- In general, confined bubble curtains attain better noise attenuation levels in areas of high current than unconfined bubble curtains. If an unconfined device is used, high current velocity may sweep bubbles away from the pile, resulting in reduced levels of noise attenuation.

- Softer substrates may allow for a better seal for the device, preventing leakage of air bubbles and escape of sound waves. This increases the effectiveness of the device. Softer substrates also provide additional attenuation of noise traveling through the substrate.
- Flat bottom topography provides a better seal, enhancing effectiveness of the noise attenuation device, whereas sloped or undulating terrain reduces or eliminates its effectiveness.
- Air bubbles must be close to the pile; otherwise, sound may propagate into the water, reducing the effectiveness of the device.
- Harder substrates may transmit ground-borne noise and propagate it into the water column.

2.5.3 Range of Observed Attenuation – Impact Pile Driving

The literature presents a wide array of observed attenuation results. The variability in attenuation levels is due to variation in effectiveness due to variation in design, as well as differences in site conditions and difficulty in properly installing and operating in-water attenuation devices. The text below summarizes the observed attenuation achieved by various devices.

2.5.3.1 Bubble Curtains

The Washington State Ferries Reference Biological Assessment (WSF 2009) cites the following projects and observed attenuation rates:

- The Mukilteo test pile project used an unconfined bubble curtain and attained on average a 17 to 23 dB reduction of peak and RMS SPLs when driving 36-inch steel pile. The bubble curtain also reduced single-strike SELs from 184 dB to 160–162 dB (noise reduction of 22 to 24 dB SEL) (MacGillvary et al 2007; Laughlin 2007).
- The Anacortes Ferry Terminal used the same unconfined bubble curtain from the Mukilteo project and achieved a 3 to 11 dB reduction in peak and RMS SPLs when driving 36-inch steel pile (Sexton 2007).
- At Bainbridge Island Ferry Terminal, an unconfined bubble curtain attained a 3 to 14 dB reduction of peak and RMS SPLs during impact driving of 24-inch steel pile (Laughlin 2005a).
- At Friday Harbor Ferry Terminal, an unconfined bubble curtain attained only 1 to 3 dB reduction of peak and RMS SPLs during impact driving of 24-inch steel pile (Laughlin 2005b).

The Biological Assessment Preparation Advanced Training Manual (Version 10-08) (WSDOT 2008) cites all of the studies listed above, as well as the following:

- Reyff (2003) observed noise reductions of 6 to 20 dB peak and 3 to 10 dB RMS when driving 8.5-foot-diameter pile and using a bubble curtain.
- Thorson and Reyff (2004) observed reductions in peak SPLs of 5 to 20 dB using a bubble curtain.
- Vagle (2003) observed reductions of 18 to 30 dB using a bubble curtain during four pile-driving projects in Canada.

- The manual notes that in Washington State, attenuation devices have resulted in average reductions in SPLs of approximately 9 dB (Laughlin 2008).

From the Endangered Species Act Section 7 Consultation: Biological Opinion – Manette Bridge Replacement, Kitsap County Washington (USFWS 2009):[5]

- Laughlin (2006) observed a maximum 17 dB peak of noise reduction while driving steel pile using an unconfined bubble curtain in combination with a non-standard nylon pile cap material in an embayment of the Columbia River.
- Houghton and Smith (2005) measured reductions of 10 to 15 dB of source sound levels while driving 24-inch steel pile at a marina in Washington.
- This Biological Opinion (BO) concurred that a confined bubble curtain could reasonably reduce source sound levels by 10 dB. Reductions in source sound levels will be confirmed by hydroacoustic monitoring.

From Final Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish (Caltrans 2009):[6]

- At the Benicia-Martinez Bridge, a bubble curtain consisting of nine stacked unconfined rings achieved from 15 to greater than 30 dB of attenuation in deep water and in strong current.
- An unconfined bubble curtain at San Francisco-Oakland Bay Bridge attained only 0 to 2 dB of attenuation while driving 8.5-foot-diameter hollow steel pile. Poor attenuation was explained by high currents and a curtain that was oversized relative to the size of the pile.
    - Later re-strikes of the same pile in this location used an improved, two-stage unconfined bubble curtain, showing significant reductions of 5 to 20 dB. The level of attenuation varied with the relationship to the current, with greater attenuation in the upstream direction (Reyff 2003).
    - Test pile driving in this location also used a confined bubble curtain made from proprietary fabric. With the device in use, monitors observed 5 to 10 dB of noise attenuation for one pile located in a water depth of less than 10 m.
- Various other pile-driving projects in California achieved 0 to 5 dB attenuation, with even higher levels (0 to 15 dB) in low current.
- Wharf repair in the San Francisco Bay region required driving of concrete pile and observed 5 to 15 dB of reduction in low current.
- At the Humboldt Bay Bridges project, using both confined and unconfined bubble curtains, devices achieved at best 10 to 15 dB of noise reduction.
- Caltrans offers the following generalizations:

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[5] Note: The authors did not specify whether the metrics were dB peak, RMS, or SEL.

[6] Note: The authors did not specify whether the metrics were dB peak, RMS, or SEL. However, Jim Laughlin has had numerous personal communications with the authors of these studies, and he advises to assume that all metrics refer to peak SPLs (Laughlin 2009 personal communication).

- For steel or concrete pile 24 inches in diameter or less, bubble curtains will generally reduce sound levels by 5 dB.
- For steel pile measuring 24 to 48 inches, bubble curtains may reduce sound levels by about 10 dB.
- For piles greater than 48 inches in diameter, bubble curtains may reduce sound levels by about 20 dB.
- As a general rule, reductions of greater than 10 dB cannot be reliably predicted.

Jim Laughlin, WSDOT acoustics specialist, has observed that, on average, unconfined bubble curtains typically achieve 9 dB of attenuation while confined bubble curtains achieve 12 dB (Laughlin 2008 personal communication).

2.5.3.2 Isolated Pile/TNAP

The isolated pile technique is known to provide a high level of noise attenuation. The WSDOT Biological Assessment Manual (WSDOT 2008) described construction of the Benicia-Martinez Bridge in California (Reyff et al. 2002), in which an isolated pile with a confined bubble curtain achieved noise reductions of 23 to 24 dB peak and 22 to 28 dB RMS. In this study, the system consisted of a 3.8-m-diameter sleeve lined with a 2.5-cm layer of rigid foam. In a personal communication with Jim Laughlin, WSDOT acoustics specialist, Reyff stated that there was no significant difference between a confined and an unconfined bubble curtain at this location (Reyff 2005 personal communication).

Jim Laughlin, WSDOT acoustics specialist, estimates that a foam-lined temporary noise-attenuation pile (TNAP) likely achieves 15 dB of attenuation (Laughlin 2009 personal communication).

2.5.3.3 Cofferdams

The WSDOT Biological Assessment Manual (WSDOT 2008) notes that a dewatered cofferdam may provide the highest levels of sound level reduction of any of the noise attenuation devices. Caltrans (2009) states that dewatered cofferdams provide reduction at levels at least as great as bubble curtains.

During construction of the San Francisco-Oakland Bay Bridge, a dewatered cofferdam achieved 20 to 30 dB of attenuation in all directions except for the down-current direction, where only 5 to 10 dB reduction occurred (Caltrans 2007). In comparison to a bubble curtain used in the same location during test pile driving, the dewatered cofferdam attenuated 5 to 10 dB more noise at 100 m south of the pile, 3 to 5 dB more at 500 m to the south, and 2 dB more at 200 m to the north.

Cofferdams that are not fully dewatered provide only low levels of noise reduction (WSDOT 2008).

2.6 Impact Pile Driving – Effects on Listed Fish

Teleost fish[7] hear by detecting particle motion in the water using their inner ear. In addition, they have an organ system called the lateral line system that detects aquatic particle motion (Hastings and Popper 2005) at frequencies below 200 hertz (Hz) (Au and Hastings 2008). Some fish species, such as salmon and trout, are known as hearing generalists (Caltrans 2009) that hear sound mainly through particle motion in the inner ear, but whose swim bladders may also contribute impulses (Hastings and Popper 2005). These fish may not be sensitive to sound pressure. Other fish species, such as lake chub, are known as hearing specialists (Caltrans 2009). Hearing specialists have a special anatomical connection between the swim bladder and inner ear (or close to the inner ear) that stimulates the inner ear in response to pressure in these gas-filled structures (Au and Hastings 2008). The inner ear senses both particle motion and acoustic pressure from the bladder. This system causes hearing specialists to be more sensitive to sound pressure (Au and Hastings 2008).

Impact pile driving produces an impulsive sound and elevates underwater sound to levels that may cause behavioral disturbance, injury, or mortality in fish (Hastings and Popper 2005). The level of effect depends on numerous factors, including the intensity, frequency, and duration of sound and the size of the fish (Caltrans 2009). However, there are only a limited number of studies on this topic, and even these are not always in agreement about the effects of pile driving on fish. Peer-reviewed literature does indicate that elevated sound levels can alter hearing capabilities, cause damage to auditory and non-auditory tissues, or result in death. However, most of this literature refers to blast studies, rather than pile driving, and there are no peer-reviewed articles providing a clear relationship between impact pile driving and injury or hearing loss (Hastings and Popper 2005). The non-peer-reviewed literature does show a link between pile driving, tissue injury, and fish mortality (Abbott and Bing-Sawyer 2002; Caltrans 2004, as cited in Hastings and Popper 2005). Other studies show no statistically significant difference in mortality or injury to fish between the control group and groups exposed to impact pile driving (Nedwell et al. 2003 and Abbott et al. 2004, as cited in Hastings and Popper 2005 and Ruggerone et al. 2008, as cited in Popper and Hastings 2009).

2.6.1 Injury or Mortality

Impact pile driving may result in a wide range of lethal and sublethal injuries. Physical injury may lead to death within minutes or days. Fish kills have been documented during impact driving of steel pile in California, Washington, and Vancouver, British Columbia (WSF 2009). Sublethal effects may limit the ability to perform basic life functions (USFWS 2009).

Hastings and Popper (2005) note that studies about injury to fish are generally centered on teleosts (ray-finned fishes such as salmon, trout, and smelt) and may not apply to more primitive chondrostean fish (such as green sturgeon).

2.6.1.1 Injury to Non-Auditory Tissues

Most fish move vertically through the water column using an air-filled swim bladder. Depending on the type of swim bladder system they have, fish are categorized as either physostomous or

[7] Hearing studies of bony fish (*Osteichthyes*) have been almost exclusively conducted on *Teleostei* of the subclass *Actinopterygii* (Au and Hastings 2008). All fish in this assessment are bony fish in the subdivision Teleostei.

physoclistous. Salmon, trout, and sturgeon are physostomous fish. They have ducted swim bladders, connected directly to the esophagus through a vessel. These fish can release air from the swim bladder directly through the mouth. Fish with non-ducted swim bladders (physoclistous fish) perform gas exchange from the swim bladder through the vascular system.

There are few studies documenting the effects of pile-driving noise on swim bladders; however, it is known that during periods of intense underwater sound, sound pressure may cause rapid inflation and deflation of the swim bladder, resulting in injury or rupture of the swim bladder in both physostomous and physoclistous fish. Tearing of the swim bladder can lead to loss of hearing in hearing specialists, loss of control over vertical movement, or death (WSDOT 2008). Hastings and Popper (2005) suggested that physostomous fish were less sensitive to intense pressure because they could more easily release pressurized gas. Salmon, steelhead, bull trout, and green sturgeon are physostomes and could presumably be subject to swim bladder damage after exposure to pile driving noise, but they are less sensitive to intense underwater sound than physoclists (Caltrans 2009). Eulachon do not have a swim bladder (Gauthier and Horne 2004). Hastings and Popper (2005) and Popper and Hastings (2009) caution that most research related to this type of injury cannot be easily applied to fish that lack swim bladders, but it is possible that fish with no swim bladders have relatively low sensitivity to sound (Popper and Fay 1993). Presumably, eulachon could be less susceptible to some types of non-auditory tissue damage because they lack a swim bladder (Goertner et al. 1994).

Other studies have observed that loud sound levels may cause damage to the skin, nerves, and eyes of fish (Caltrans 2009). Elevated sound levels may also result in the formation of gas bubbles in tissue, causing inflammation, cellular damage (Vlahakis and Hubmayr 2000; Stotz and Colby 2001, both cited in USFWS 2009), and blockage or rupture of blood vessels (Crum and Mao 1996, cited in USFWS 2009).

The literature shows that non-auditory tissue damage is a function of sound dosage (SEL) rather than peak sound levels (Yelverton et al. 1975; Wiley et al. 1981; Teleki and Chamberlain 1978; Hastings 1990, 1995; Stuhmiller et al. 1996; Govoni et al. 2003, all as cited in Carlson et al. 2007). Smaller fish are more susceptible to non-auditory tissue damage than larger fish (Carlson et al. 2007).

2.6.1.2 Auditory Effects – Hearing Loss and Tissue Damage

There are few direct, peer-reviewed studies on the effect of loud sounds on the hearing capabilities of fish (Caltrans 2009), and those that have been conducted may not be applicable to pile driving (Hastings and Popper 2005). However, loud sounds may lead to hearing loss in fish. Sensory hair cells located in the inner ear can become damaged after exposure to loud sounds (Hastings and Popper 2005). Hair cells regenerate continually and there is some evidence that these cells can repair themselves after exposure to loud sounds (Smith et al. 2006; Meyers and Corwin 2008).

Intense sound may lead to temporary loss of hearing in fish, also known as temporary threshold shift (TTS). TTS represents fatigue of the hair cells in the inner ear and is not considered tissue damage (Carlson et al. 2007). Generally, it occurs at a lower level of sound than does auditory tissue damage (Caltrans 2009). Caltrans (2009) notes that fish may recover from TTS within minutes or days. Popper et al. (2005) exposed hearing generalists northern pike and broad whitefish to high-intensity sounds. Northern pike showed no significant TTS. Broad whitefish experienced significant TTS at some frequencies and within 18 hours of exposure showed no significant TTS compared to controls. The same study found that hearing specialists were susceptible to TTS for a period of 18 to 24 hours after exposure (Popper et al. 2005). Accordingly, a rest period with no pile-driving has been required by NMFS in recent biological opinions. This rest period is intended to allow fish to recover from TTS or to move through areas subject to elevated sound levels. Of the species of interest that use the Columbia River and North Portland Harbor, salmon and trout are hearing generalists and are less susceptible to TTS. Larger fish are more susceptible to TTS than smaller fish (Caltrans 2009). As hearing specialists, eulachon are presumably more sensitive to TTS. Although several studies document the relationship between noise exposure and TTS, there are no data that quantify the precise noise levels that cause onset of TTS in fish (Carlson et al. 2007).

For some organisms, intense sound may reach levels that cause permanent threshold shift (PTS): permanent hearing loss resulting from the irreversible death of sensory hair cells in the inner ear (Caltrans 2009). This phenomenon is poorly understood in fish. Three peer-reviewed studies (Enger 1981; Hastings et al. 1996; McCauley et al. 2003) document high-intensity noise destroying the sensory cells of fish. These studies all showed destruction of sensory cells in some instances of exposure to sound above the auditory threshold of the subject fish. However, none examined the relationship between destruction of hair cells and PTS (Hastings and Popper 1995).

Auditory damage may result in a general decrease in fitness, foraging success, ability to avoid predators, and ability to communicate (Caltrans 2009).

2.6.1.3 Studies Related to Injury of Fish in Response to Pile Driving Noise

Hastings and Popper (2005) reviewed and summarized the following case studies:

- San Francisco-Oakland Bay Bridge Pile Driving Installation Project (Caltrans 2001): Pile-driving noise resulted in mortality of fish found within 50 m of the pile. Dead fish exhibited injuries such as bleeding and damage to the swim bladder. Caged shiner surfperch (*Cymatogaster aggregata*) interspersed throughout the study area experienced higher injury and mortality closer to the source than further away. The study did not make conclusions about other factors, such as pile-driving duration or hammer energy. Distance effects may have been confounded by noise flanking. The study did not specify the noise levels to which fish were exposed.
- Abbott and Bing-Sawyer (2002): Reported that caged Sacramento blackfish (*Orthodon microlepidotus*) experienced auditory damage when exposed to pile-driving noise at 193 dB peak and experienced no damage when exposed to pile-driving noise at 183 dB peak. It should be noted that these sound levels were extrapolated and not actually measured at the cages. Therefore, it is difficult to draw a direct link between these noise levels and the potential for injury in fish. The authors observed no behavioral effects but noted that they did not have suitable facilities in which to perform behavioral observations.
- Nedwell et al. (2003): Demonstrated that caged brown trout (*Salmo trutta*) were not killed when exposed to 134 dB at 400 m from the source during pile driving.
- Caltrans (2004): Exposed caged shiner surfperch and steelhead (*Oncorhynchus mykiss*) to impact pile driving from 23 to 314 m from the operation. The authors reported higher levels of trauma in test fish than in control fish, but no mortalities could be directly attributed to pile driving. The study did not specify the noise levels to which fish were exposed.

- Port of Oakland Preliminary Study (Abbott 2004; Marty 2004): Exposed caged shiner perch, Chinook salmon, and northern anchovy to impact driving of 24-inch-diameter concrete pile. Later necropsies revealed no physical differences between the test group and the control group. The study also concluded that there were no behavioral differences, but only looked at behaviors occurring after (and not during) the sound impulse. The study did not specify the noise levels to which fish were exposed.
- Two unpublished studies observed higher abundance of fish at times when pile driving was not occurring than during periods of pile driving (Feist et al. 1992; Bonar 1995). However, these were unquantified, uncontrolled observations of free-swimming fish, rather than direct observations of exposure to specified sound levels at various distances.

2.6.2 Behavioral Effects

Literature related to the effect of pile driving on fish behavior is extremely limited and somewhat conflicting. Caltrans (2009) cites the following studies:

- Engås et al. (1996) and Engås and Løkkeborg (2002) noted a decreased harvest rate of haddock and cod for several days after underwater air gun noise occurred. Neither study provided a direct causal link between noise and decrease in harvest, however.
- Slotte et al. (2004) noted that fish appear to move deeper into the water column in response to air gun noise. The study also showed a decrease in harvest of pelagic fish in the area exposed to air gun noise. Additionally, the study suggested that fish would not enter the area of elevated noise.
- Gausland (2003) refuted these findings, attributing the results to normal annual variation. This article was not peer reviewed.
- Wardle et al. (2001) found no evidence of avoidance or other behavioral changes in response to noise produced by air guns.

Hastings and Popper (2005) cited the above studies plus:

- Skalski et al. (1992) reported that fishes (species not specified) show a startle response at 160 dB and that rockfish harvest decreases after one air gun blast measuring 186 to 191 dB.

Longer-term behavioral response to pile driving has not been studied and is virtually unknown (Caltrans 2009; Hastings and Popper 2005).

The current guidance from NMFS for behavioral effects is 150 dB RMS, the level at which behavioral effects are thought to occur. Sound above this level is probably unavoidable during pile driving, because in general, pile driving produces noise over 150 dB RMS even with the use of a noise attenuation device (Table 2-2) (WSDOT 2008). Therefore, it can be assumed that impact pile driving could potentially result in some level of behavioral disturbance. Effects could be relatively minor, limited to startling, disruption in feeding, or avoidance of the action area (Wardle et al. 2001). Other effects could be more significant, with consequences for survival and reproduction. For example, while exposure to sound levels above 150 dB RMS is not likely to cause direct mortality or injury, it could result in an impaired ability to avoid predators, indirectly resulting in death. Additionally, avoidance of the action area could presumably cause delays in migration. Migration delays, in turn, may present a variety of risks for fish including depletion of energy reserves; delayed or reduced spawning; increased exposure to predation, disease, and thermal stress; disruption of arrival timing to the estuary (which may desynchronize arrival with prey availability); and an increase in residualism in some steelhead and Chinook (NMFS 2008c).

2.6.3 Physiological Stress

Physiological stress in response to elevated sound levels is poorly understood in fish. In general, stress is known to increase susceptibility to infection and predation. However, there is no clear link between elevated sound levels and stress (Hastings and Popper 2005). In their review of the effects of noise on fish, Hastings and Popper (2005) only cite two studies on physiological stress. Gilham and Baker (1985, as cited in Hastings and Popper 2005) measured physiological stress (high cortisol levels) in rainbow trout for 1 to 5 days after exposure to high levels of vibration in an aquarium. Wysocki et al. (2006) detected physiological stress (high cortisol levels) in three species of freshwater fish in response to shipping noise. However, Smith et al. (2004) found no significant stress response of goldfish to elevated sound.

2.6.4 Eggs and Larvae

Eggs are stationary, unable to avoid sound impulses, and therefore could be exposed to excessive durations of noise. Likewise, larvae may have little or no motility and therefore, could be exposed to high levels of noise for a longer duration than other life stages of fish.

Data on the effects of intense sound on eggs and larvae are extremely limited. Most studies focus on explosive sound or mechanical shock (Hastings and Popper 2005). These types of noise have very different characteristics than pile-driving noise and therefore, may not be relevant to the CRC project.

Hastings and Popper (2005) cite the following studies:

- Jensen and Alderice (1989) performed controlled drops of salmon and trout eggs. Results showed high mortality of eggs that had not yet started to divide.
- Post et al. (1974) dropped rainbow trout eggs and did not detect any effect on eggs at any stage of development.
- Smirnov (1959) performed mechanical agitation of salmon eggs and found varying levels of mortality at stages of development occurring after cell division.
- Banner and Hyatt (1973) found that eggs of *Cyprinodon variegatus* exposed to sound at 15 dB above ambient levels had higher mortality that the control group. However, the study found no effect on *Cyprinodon variegatus* fry or *Fundulus similus* eggs or fry. Larvae of both species demonstrated significantly impaired development after exposure to elevated sound.
- Bennett et al. (1994) found that eggs and embryos exposed to 115 to 140 dB peak did not demonstrate mortality or delayed development. This study was not peer reviewed.
- Kostyuchenko (1973) reported damage to the eggs of marine fishes after exposure to seismic air gun blasts at a distance of 20 m.

- Booman et al. (1996) found significant mortality of the eggs, larvae, and fry of marine species after exposure to seismic air-gun blasts. Most mortality occurred at a distance of 1.4 m from the source, but significant effects occurred at a distance of 5 m.

Hastings and Popper (2005) cautioned that it is impossible to draw any conclusions about the effects of elevated sound on eggs and larvae due to the lack of knowledge on this subject.

2.7 Vibratory Pile Driving – Effects on Listed Fish

Vibratory pile driving produces lower peak sound levels, and this generally results in fewer injuries to fish (USFWS 2009) (Table 2-2 and Table 2-3). Rise time is also much slower during vibratory pile driving, decreasing the potential for injury (Carlson et al. 2001 and Nedwell and Edwards 2002, as cited in USFWS 2009). During vibratory pile driving, SPLs may not exceed background levels (USFWS 2009; WSF 2009). Vibratory installation of steel piles in a California river did not produce SPLs that were greater than background levels created by the current (measured at 170 dB peak and 155 dB RMS) (Reyff 2006, as cited in USFWS 2009; Caltrans 2007). Although vibratory hammers produce less peak sound levels than impact hammers, they may generate more accumulated SEL in cases where they require more time to install the pile (Caltrans 2009).

USFWS states that there are no documented kills attributed to the use of a vibratory hammer (USFWS 2004a, as cited in WSF 2009).

Currently, there are no thresholds established by the FHWG for noise levels generated by vibratory pile driving that are likely to cause injury to fish. NMFS has a disturbance guidance of 150 db RMS for all noise types.

Few studies on the effects of vibratory pile installation exist. Nedwell and Edwards (2003) exposed caged brown trout to sound from vibratory pile installation. The study found that sound levels did not exceed ambient levels at 417 m from the source. Additionally, the caged trout exhibited no responses to vibratory pile driving at any of the following distances: 25 m, 50 m, 100 m, and 200 m. Carlson (1996) observed salmon and steelhead responses to vibratory pile driving in the Columbia River, noting that avoidance response by salmon and steelhead is unlikely to extend beyond 6 to 9 m from vibratory pile installation. Carlson (1996) concluded that, due to the short range of this effect, vibratory pile driving is unlikely to have a significant impact on the migration behavior of juvenile salmonids.

However, work by Hastings (1995, as cited in Hastings and Popper 2005) and Hastings et al. 1996 found that continuous sounds might cause auditory damage, unconsciousness, and even death in fish. Hastings (1995) found that damage to the sensory hair cells of goldfish occurred after exposure to continuous tones at 189 dB peak, 192 dB peak, and 204 dB peak at 250 Hz; and 197 dB peak at 500 Hz. The same study showed no auditory damage to goldfish at 182 dB peak at 500 Hz. Hastings et al. (1996) exposed several oscar to continuous a 300-Hz pure tone at 180 dB peak, observing no auditory damage one day after exposure but evident auditory damage after four days. This indicates that exposure to continuous noise may result in delayed damage to auditory structures. Blue gouramis experienced “acoustical stunning” and loss of consciousness after exposure to a 150-Hz pure tone at 198 dB peak for approximately 8 minutes (Hastings 1990, 1995; both cited in Hastings and Popper 2005). In the same study, goldfish died following 2-hour continuous wave exposures at 250 Hz and 204 dB peak, and blue gouramis died after 0.5-hour continuous wave exposures at 150 Hz and 198 dB peak.

3. Calculating Area of Effect and Fish Exposure

This section presents the CRC project's approach to estimating initial sound pressure levels, the types and effectiveness of noise attenuation measures, and how the area of effect was calculated. Assumptions for calculation input variables are presented. This section concludes with a description of how CRC calculates exposure factors on a weekly basis throughout a construction year.

Construction of the bridges over the Columbia River and North Portland Harbor requires the in-water installation of temporary piles that will produce sound levels expected to exceed hydroacoustic thresholds for the onset of injury and the behavior disturbance guidance for fish species. Over 1,500 temporary steel pipe piles will be installed for temporary work platforms and oscillator support structures. Use of two size classes of piles: 18- to 24-inch piles and 36- to 48-inch are anticipated. These piles must be load bearing and therefore will need to be impact driven to ensure they have the proper load-bearing capacity. We refer to establishing load-bearing capacity through use of an impact hammer as "proofing."

To reduce potential hydroacoustic impacts to fish from impact pile driving, the project is applying the following minimization measures:

1. Temporary piles will be vibrated to refusal first (approximately 5 to 30 minutes per pile), then driven and proofed with an impact hammer.
2. A noise attenuation device will be used for all impact driving of pile (with the exception of monitoring activities that may require attenuation devices to be turned off for very short periods).
3. Impact driving will only occur during a 31-week in-water work window from September 15 through April 15.
4. Hydroacoustic monitoring will ensure exposure to fish as described in this section will not be exceeded.

These minimization measures are described in Section 7 of this document.

To calculate pile driving noise exposure to listed species in the Columbia River and North Portland Harbor we employed the following steps:

- Estimated source sound levels for 18- to 24-inch piles and 36- to 48-inch piles.
- Factored reduction of source sound levels due to use of a noise attenuation device (impact driving only).
- Determined the appropriate model and input values for calculating an area of effect.
- Developed probable construction sequences to model pile sizes and numbers impact driven on a daily and weekly basis for every year of construction.

- Used the moving fish model to calculate the distances to onset of injury thresholds and behavioral disturbance zones to fish based on the impact pile driving sequences modeled, fish speed and size.
- Calculated the proportion of the channel affected (from output in preceding bullet) and the proportion of day and week affected (from the construction sequences).
- Calculated the weekly exposure factors for each construction sequence modeled.
- Calculated exposure to the proportion of adults and juveniles of each DPS/ESU present in any week of construction, in each year of construction and overall for the project duration. The following equation was used to calculate weekly exposure:

  Weekly Fish Exposure = Weekly Proportion of Run x Weekly Exposure Factor

The sections below describe the analysis for each of the preceding points.

3.1 Estimating Source Sound Levels

Source sound levels from impact pile driving are used in calculating the area of effect for injury, mortality, and disturbance to fish.

Table 2-2 in Section 2.4.1 outlines typical source sound levels measured during impact pile driving. Sound levels are highly dependent on environmental site conditions. Therefore, the team considered published hydroacoustic monitoring data for projects with similar site conditions as the CRC project. WSDOT and Caltrans[8] have compiled hydroacoustic monitoring data from in-water impact pile driving. We did not identify projects with similar site conditions and hydroacoustic monitoring data in the Columbia River.

A review of WSDOT and Caltrans projects containing in-water pile driving found projects with the most similar substrates and depths in California; however, only one project used 48-inch pile, the largest size in the CRC project. This work occurred in the Russian River, which is only 15 m wide and 0.6 m deep at the project location. Therefore, the results are not applicable to the CRC project. For lack of relevant data on 48-inch pile, we instead looked at projects that drove 36-inch pile, using the highest noise levels encountered as proxy values for 48-inch pile.

The Humboldt Bay Bridge project, constructed in Eureka, California in 2004, conducted unattenuated impact pile driving of 36-inch pile (Caltrans 2007). Water depth and relative size of the water body at this site were similar to the CRC action area. Humboldt Bay has a maximum depth of approximately 12 m, while the CRC action area has a maximum depth of approximately 18 m. Both are large, open water bodies. The study observed the following sound levels at a distance of 10 m from the source and at a depth of 10 m: 210 dB peak, 193 dB RMS, and 183 dB SEL.

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[8] The Compendium of Pile Driving Sound Data (Caltrans 2007) contains the most comprehensive information about measured levels of underwater sound encountered during pile driving. The report presents case studies of actual in-water pile driving, including project-specific information about pile size, pile type, water depth, distance to monitoring point, use of attenuation device, and environmental site conditions.

A Washington project (Laughlin 2007) measured sound levels from 36-inch steel pile installation in Puget Sound and observed the following results: 214 dB peak, 201 dB RMS, and 186 dB SEL. These values are presented in the WSDOT Biological Assessment Preparation Manual (WSDOT 2008). Site conditions at Puget Sound are somewhat comparable to the Columbia River, as both are large, with similar depths.

The available data indicate that highest levels of noise produced by impact driving of 36-inch pile would be 214 dB peak, 201 dB RMS, and 186 dB single-strike SEL at 10 m from the source. The CRC team adopted these values as the source noise levels for impact pile driving 36- to 48-inch piles[9].

The CRC project will also drive 18- to 24-inch diameter steel pile. In order to use comparable data between the different pile sizes proposed for the CRC project, we chose to adopt the average source sound levels presented in the WSDOT Biological Assessment Preparation Manual for 18- to 24-inch piles: 212 dB peak, 189 dB RMS, and 181 dB single-strike SEL at 10 m from the source.

3.2 Effectiveness of Noise Attenuation Devices

Noise attenuation devices decrease sound levels from impact pile driving, thereby potentially decreasing the area of effect.

The project will use a noise attenuation device during impact pile driving to minimize sound levels. The actual type of noise attenuation device(s) will be determined after further research by the CRC project team and in coordination with resource agencies. This section outlines the rationale by which the team determined that 10 dB of attenuation is attainable and would be achieved on the CRC project.

Actual effectiveness of noise attenuation devices depends on a variety of site-specific conditions, as outlined in Section 2.5. In order to determine the level of noise attenuation achievable for the CRC project, the team selected two reference sites with environmental conditions similar to the CRC project area. We considered the following four site-specific factors:

- Water depth: Water depth in the Columbia River ranges from 0 to 18 m; water depth in North Portland Harbor ranges from 0 to 7.5 m.
- Current velocity: The project is in an area with a current velocity of greater than 0.6 m/s. Therefore, we considered attenuation levels achieved from use of a confined bubble curtain.
- Substrate type: The substrate is soft (unconsolidated sand above the Troutdale layer); therefore, ground-borne sound propagation is not be expected to be high, as softer surfaces tend to dampen sound more than hard surfaces.

[9] The CRC project team also looked at using sound level numbers from larger pile, such as 60-inch pile. At 10 m, the sound levels for this size pile were recorded as 210 dB peak, 195 dB RMS, and 185 dB SEL. The same sound levels were recorded for 66-inch pile, except no measurements were collected for the SEL element. The sound levels for these larger piles are more than for the 36-inch piles presented as the surrogate for the 48-inch piles. As such, the use of the 36-inch piles measurements provide conservative estimate.

- Bottom seal: The sand substrate and relatively flat topography of the main channel and North Portland Harbor river bottoms will likely allow for a good seal of the noise attenuation device with the bottom. Divers will perform underwater surveys before impact pile driving to remove any wood piles (or other items potentially located on the stream bottom) that would interfere with the bottom seal of the noise attenuation device.

There are only a few pile driving projects that have monitored impact pile driving with noise attenuation, and even fewer that occurred in conditions similar to those in the CRC action area. There are two case studies that have environmental conditions reasonably similar to conditions at the CRC project site: The San Francisco-Oakland Bay Bridge Pile Installation Demonstration Program and the Benicia-Martinez Bridge (Caltrans 2007). Both studies demonstrate that 10 dB of reduction in source sound levels has been attained using various kinds of noise attenuation devices under environmental conditions similar to those in the CRC project area. For this reason, the team believes that a 10 dB reduction of sound pressure levels on the CRC project is attainable with the use of an attenuation device.

3.2.1 San Francisco-Oakland Bay Bridge Pile Installation Demonstration Program and Bridge Construction

In 2000, the San Francisco-Oakland Bay Bridge Pile Installation Demonstration Program (PIDP) drove 96-inch steel pile into the floor of San Francisco Bay. The project used a Gunderboom® System, a confined bubble curtain made from proprietary fabric, to attenuate noise from pile driving. With the device in use, monitors observed 5 to 10 dB of noise attenuation for one pile located in a water depth of less than 10 m. The project also used a single-ring bubble curtain to install battered 96-inch steel pile in roughly 12 m of water. This device achieved only 0 to 2 dB of noise attenuation.

In 2003, Caltrans conducted the PIDP restrike project to test the stability of the piles driven in 2000 and the effectiveness of a two-ring bubble curtain (Caltrans 2009). Results were mixed, but attenuation ranged from 5 to 20 dB, representing a significant improvement over the single-ring curtain used in 2000. Noise attenuation varied with the current, with 5 to 7 dB of attenuation on the south (down-current) side and 20 dB of attenuation on the north (up-current) side.

During pile driving for subsequent construction of the San Francisco-Oakland Bay Bridge, a two-tiered bubble curtain attained 5 to 20 dB of peak SPL attenuation. The device achieved these attenuation levels despite 10-m deep water and strong currents, circumstances that tend to enhance sound propagation and reduce the effectiveness of attenuation devices.

3.2.2 Benicia-Martinez Bridge

The Benicia-Martinez Bridge project in California drove large steel piles measuring approximately 96 inches in diameter. This project used two kinds of noise attenuation devices (Caltrans 2009). With an unconfined bubble curtain consisting of nine-tiered rings, monitors observed attenuation from 15 dB to more than 30 dB. The project also used a confined-system isolation pile consisting of a 3.7-m diameter steel pile casing. This confined system achieved an attenuation level of 20 to 25 dB, either with bubbles or in a dewatered condition. Site conditions on the Benicia-Martinez project included high-velocity current, which tends to reduce effectiveness of the bubble curtain.

3.3 Calculating Area of Effect

The CRC project calculated the distances to injury thresholds from peak noise and to onset of behavioral disturbance based on likely daily impact pile driving activities. CRC uses the distance to the onset of injury threshold from accumulated SEL as a key component in calculating the exposure factor and to estimate potential impacts to fish runs in the project area.

As described in Section 2.3 of this document, NMFS has developed calculators for modeling the hydroacoustic area of effect for both stationary and moving fish. The area of effect obtained through the stationary fish model varies based on number of pile strikes when other variables such as single-strike SEL and fish mass remain the same. In contrast, the area of effect for cumulative SEL obtained through the moving fish model increase or decrease based on fish speed and number of pile strikes while other variables remain the same.

For example, in the moving fish model, the faster a fish moves through an area, the less time it has to accumulate potentially injurious sound energy. The effect of speed on the area of effect is more noticeable at higher fish movement speeds (nearing 1.0 m/s), whereas the area of effect for fish moving 0.1 m/s are substantially the same as the area of effect calculated using the stationary fish model. Using an example of an attenuated 36- to 48-inch diameter pile struck 300 times, the pile driving time would be approximately 7.5 minutes. A fish (with a mass of over 2 g) moving at a speed of 0.8 m/s would travel approximately 360 m in a 7.5-minute period. If that fish passed within approximately 47 m of the driven pile, it could receive enough sound energy for injury to occur. If the fish were traveling at only 0.6 m/s, then it could experience enough sound energy for injury to occur within approximately 58 m from the pile. If the fish were traveling at 0.1 m/s or was stationary, then it could experience enough noise energy for injury to occur within approximately 83 m from the pile. If the fish passed inside of the threshold distance for its given speed, injury would be more likely.

On August 17, 2009, the CRC team met with Dr. John Stadler, a NMFS underwater acoustic specialist, and Devin Simmons, the CRC NMFS liaison. The purpose of the meeting was to present a preliminary pile driving scenario to NMFS and to obtain guidance on which model would be most appropriate for use on the CRC project. At that meeting, NMFS agreed that the moving fish model would be appropriate for the fish species and life history stages that are actively migrating through the action area. The CRC project then adopted the moving fish model and incorporated project-specific elements into it.

3.3.1 Model Input Variables

Model input variables and their associated values assigned by CRC are described below. These variables include:

- Fish size,
- Estimated source sound levels,
- Transmission loss,
- Number of pile strikes,
- Strike interval, and
- Transit rate by fish

Only fish size, source sound levels, and transmission loss are used to calculate distances to peak injury and onset of behavioral disturbance. All the variables are used in calculating the distance to onset of injury using accumulated SEL. Using the CRC approach, different combinations of any of these variables will yield different areas of effect and exposure factors.[10]

3.3.1.1 Fish Size

All fish were assumed to weigh over 2 grams (g) with the exceptions of juvenile chum and larval eulachon. Chum and eulachon emerge from nearby spawning sites and move downstream very soon after emergence. Juveniles of other species that pass through the project area tend to spend time rearing and gaining mass upstream of the project. The vast majority of these fish weigh over 2 g (see Section 4 of this document for more detail).

3.3.1.2 Estimated Source Noise Levels

Source peak, RMS, and single-strike SEL noise levels are estimates based on other projects as described in Section 2.4. Estimated levels for 36- to 48-inch piles are 214 dB peak, 201 dB RMS, and 186 dB SEL at a distance of 10 m from the source. Estimated values for source noise levels for 18- to 24-inch piles are 212 dB peak, 189 dB RMS, and 181 dB SEL at a distance of 10 m from the source. The team assumed that the use of an attenuation device would decrease source SPLs and SELs by 10 dB, as described in Section 3.1.

Table 3-1. Observed Underwater Noise Levels Generated by Impact Pile Driving

Type/Size of Pile	dB Peak	dB RMS	dB SEL
24-inch steel pile	212	189	181
36-inch steel pile	214	201	186

Source: WSDOT Biological Assessment Preparation Manual (WSDOT 2008).
Note: Noise levels measured at a distance of 10 m.

The sizes or combination of sizes of piles that could be driven within any one day of impact pile driving are based on construction sequencing described in Section 1.2.

3.3.1.3 Transmission Loss

No site-specific value for the transmission loss constant is available. Therefore, CRC used the default value of 15 as presented in the NMFS calculator.

3.3.1.4 Number of Pile Strikes

The contractors conducting pile driving will determine the type of impact hammer, size of pile, and type of pile. In lieu of this information, the CRC engineering team assumed the number of strikes for a representative scenario involving 18- to 24-inch- and 36- to 48-inchdiameter piles, and up to two impact pile drivers operating simultaneously. For the Columbia River construction activities, the project assumed that up to six piles per day of driving will be vibrated in until refusal, then impact driven to load-bearing capacity. CRC conservatively estimated that each pile

[10] As a simple example, a higher number of pile strikes on a small pile with a low initial SPL over a given time period may result in the same exposure factor as a lower number of pile strikes conducted on a large pile that has higher initial sound levels.

will need an average of 300 attenuated pile strikes per pile, or a maximum of 1,800 strikes per day if all six piles were installed. Table 3-2 shows the assumed composition of pile strikes that will use an attenuation device and will occur each day that pile driving occurs. Five days of impact pile driving in one week were assumed for this scenario. While other variations could occur, the CRC project team needed one scenario to place into the model for purposes of calculating impacts. For this scenario, it was assumed that a single pile driver would strike one or more 18- to 24-inch-diameter piles for 400 strikes in succession. After a break of more than one hour, it was assumed that a single pile driver then would strike one or more 36- to 48-inch piles for 800 strikes in succession. Another break of one or more hours would occur, and then two pile drivers would strike two or more 18- to 24-inch piles for a total of 200 strikes in succession. Finally, after another break of an hour or more, two pile drivers would strike two or more piles (of which at least one is a 36- to 48-inch pile) for 400 strikes in succession.[11]

In addition, the CRC project team assumed that up to 300 unattenuated pile strikes would occur one day per week of active impact pile driving for monitoring purposes or as a result of attenuation method failure.[12] Of these 300 pile strikes, 150 were assumed to be completed on 18- to 24-inch piles and 150 on 36- to 48-inch piles. Potential pile driving strike numbers for the Columbia River Bridge construction are presented in Table 3-2.

Table 3-2. Impact Pile Driving Summary for Columbia River Bridge Construction

Pile Size	Strikes per Day	Days per Week[a]	Strike Interval[b]
Without Attenuation Device			
Single pile driver: 18- to 24-inch pile	150	1	1.5
Single pile driver: 36- to 48-inch pile	150	1	1.5
With Attenuation Device			
Single pile driver: 18- to 24-inch pile	400	5	1.5
Single pile driver: 36- to 48-inch pile	800	5	1.5
Two pile drivers: each with 18- to 24-inch pile	200	5	0.75
Two pile drivers: one 18- to 24-inch pile and one 36- to 48-inch pile, or two 36- to 48-inch piles	400	5	0.75

a Days per week during active driving only.
b Measured in seconds between strikes.

For impact driving activities within North Portland Harbor, the CRC project team assumed that up to 1,800 attenuated impact pile strikes will occur per day of driving, split evenly between 18- to 24-inch and 36- to 48-inch diameter piles, and with a break of at least one hour between driving bouts. Also, due to the relatively limited nature of the driving in the North Portland Harbor, the CRC project team assumed that only 150 unattenuated pile strikes will occur one day per week of active impact pile driving for monitoring purposes or as a result of attenuation

[11] Infinite scenarios of pile size, pile strikes, and timing of those strikes could be modeled. By using the CRC analysis methods, various combinations of these element will be modeled on a daily basis during construction to ensure performance measures are met on a daily, weekly, and yearly basis.

[12] Unattenuated pile driving may occur on more than one day, but many fewer pile strikes would occur each day.

method failure. Of these 150 pile strikes, 75 were assumed to be completed on 18- to 24-inch piles and 75 on 36- to 48-inch piles. Potential pile driving strike numbers for the North Portland Harbor bridge construction are presented in Table 3-3.

Table 3-3. Impact Pile Driving Summary for North Portland Harbor Bridge Construction

Pile Size	Strikes per Day	Days per Week[a]	Strike Interval[b]
Without Attenuation Device			
Single pile driver: 18- to 24-inch pile	75	1	1.5
Single pile driver: 36- to 48-inch pile	75	1	1.5
With Attenuation Device			
Single pile driver: 18- to 24-inch pile	900	3 to 5	1.5
Single pile driver: 36- to 48-inch pile	900	2	1.5

a Days per week during active driving only.
b Measured in seconds between strikes.

As noted previously, the number of pile strikes will likely vary depending on pile size, substrate, hammer size, and other factors. The construction contractor will be required to monitor pile driving activities to calculate areas of effect and ensure that exposure factors are not exceeded.

3.3.1.5 Strike Interval

The strike interval is a variable in the accumulated SEL calculation. It is not used in calculating distances to the 206 dB Peak or 150 dB RMS boundaries. The strike interval was estimated by the engineering team from an average strike rate of 40 strikes per minute, or one strike every 1.5 seconds. This assumption is from industry standards for impact hammers, which range from 35 to 52 strikes per minute (Hammersteel 2009). When we modeled two pile drivers operating simultaneously, we assumed the strike rate averages 80 strikes per minute (double the single-strike rate), or a strike interval of 0.75 second.

3.3.1.6 Transit Rate

The transit rate is a variable in the accumulated SEL calculation for moving fish. There are few specific data on the transit rate of listed fish through the action area. We extrapolated transit rates using the best available data for both juvenile and adult salmonids (see Section 4 of this document). Based on the available data, transit rates for adult salmon are 0.1 meters per second (m/s), larval eulachon and juvenile chum are assumed to move at the speed of the current (0.6 m/s), while the remaining juvenile salmonids are 0.8 m/s.

3.3.2 Injury Threshold and Disturbance Distances

For illustrative purposes, we used the scenarios presented above to calculate the distances to the onset of injury threshold and behavioral disturbance boundary for each pier at each in-water pier complex in the Columbia River and at each bent in North Portland Harbor. In-water piers for the Columbia River are denoted as pier complexes 2 through 7 (or P2 through P7 on figures in this document). (Pier 1 is located landward on Hayden Island.)

Table 3-4 through Table 3-7 summarize the radial distances from a driven pile at which impact pile driving SPLs and SELs exceed injury threshold and disturbance guidance levels in the Columbia River and North Portland Harbor for each combination of pile size, number of drivers, threshold/guidance value, fish speed, and attenuation state. When multiple drivers are used, the radial distance was increased by 30 m to account for the estimated distance between pile drivers.

Figure 3-1 through Figure 3-13 show the areas of effect for both piers in every in-water pier complex in the Columbia River and for every bent location for the North Portland Harbor bridges. Because the figures diagram the area for both piers at each pier complex, the circular areas overlap into a rectangular shape. Note that although the distances to the injury thresholds and disturbance guidance for all piers are on one figure, actual pile driving at all piers or pier complexes will not take place simultaneously. The distances in the figures are for illustrative purposes of the area of effect only. We modeled areas of effect and potential impacts to fish with pile driving occurring at each pier according to the impact pile driving sequencing described in Section 3.3.2.1. In the sequencing modeled, the majority of pile driving occurs at one or two locations at the same pier or pier complex. About once or twice over the construction period, pile driving occurs at more than one pier complex.

When threshold and disturbance guidance distances extend into landforms (such as islands, point bars, jetties, river bends, or streambanks), the cross-channel diameter of those distances is adjusted to exclude the areas behind the landform (e.g., when piers are close to land). These adjusted values are termed by CRC to be *effective* threshold diameters when referring to cumulative SEL threshold diameters in the impact model.

Table 3-4, Figure 3-1, and Figure 3-2 present the results of calculations showing distances to peak noise thresholds for a single pile driver and for two pile drivers of 18- to 24-inch piles and 36- to 48-inch piles.

Table 3-4. Distances at Which Underwater Noise Exceeds Peak Injury Threshold Level in the Columbia River and North Portland Harbor

Impact Pile Driving	Radius
Without Attenuation Device	
18- to 24-inch pile	25 m
36- to 48-inch pile	34 m
With Attenuation Device	
Single pile driver: 18- to 24-inch pile	5 m
Single pile driver: 36- to 48-inch pile	7 m
Two pile drivers[a]: each with 18- to 24-inch pile	5 m
Two pile drivers[a]: one 18- to 24-inch pile and one 36- to 48-inch pile	7 m
Two pile drivers[a]: each with 36- to 48-inch pile	7 m

a The North Portland Harbor bridges will not use more than one impact pile driver at a time.

Table 3-5, Table 3-6, and Figure 3-3 through Figure 3-11 present the results of calculations showing distances to the cumulative SEL thresholds from impact pile driving for bridge construction. The tables presents the results of the potential scenario outlined in Table 3-2 and Table 3-3 for adult fish (mass of over 2 grams and moving 0.1 m/s), large juvenile fish (mass of over 2g and moving 0.8 m/s), and small juvenile fish (mass under 2 g and moving 0.6 m/s).