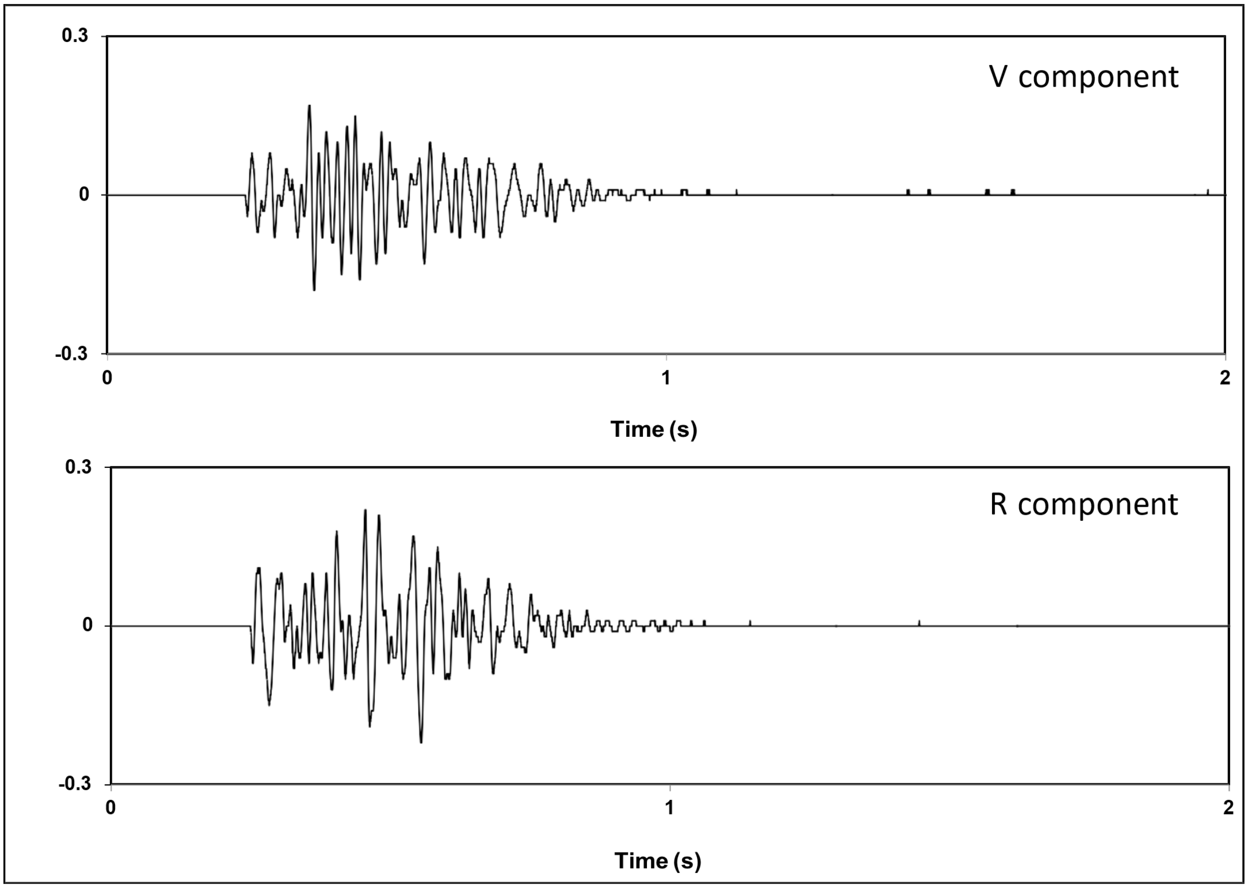
# MANAGING THE IMPACTS OF BLAST-INDUCED VIBRATION AND OVERPRESSURE ON FISH AND FISH HABITAT

Publication No. FHWA-FLH/TD-19-001 January 2019




U.S. Department
of Transportation

Federal Highway
Administration

# FOREWORD

The Federal Lands Highway (FLH) promotes development and deployment of applied research and technology applicable to solving transportation related issues on Federal Lands. The FLH provides technology delivery, innovative solutions, recommended best practices, and related information and knowledge sharing to Federal agencies, Tribal governments, and other offices within the FHWA.

The objective of this study was to produce a white paper to present an overview of both technical and management issues concerning vibrations generated by construction activities near bodies of water, and provide high-level guidance in the areas of regulatory compliance and mitigation measures that may promote timely resolution to vibration-related concerns.

This document provides information promoting environmental stewardship to the many federal and state agencies who work to avoid, minimize, or mitigate construction vibration impacts to fish and the sensitive areas of fish habitat.

---

Victoria Peters, P.E., Director, Center for Local Aid Support
Federal Highway Administration
Office of Innovative Program Delivery

**Technical Report Documentation Page**

| | | |
|---|---|---|
| 1. Report No.<br>FHWA-FLH/TD-19-001 | 2. Government Accession No. | 3. Recipient's Catalog No. |
| 4. Title and Subtitle<br>*Managing the Impacts of Blast-Induced Vibration and Overpressure on Fish and Fish Habitat* | | 5. Report Date<br>January 2019 |
| | | 6. Performing Organization Code |
| 7. Author(s)<br>Dr. Catherine T. Aimone-Martin (1)<br>Kristen D. Kolden (2) | | 8. Performing Organization Report No. |
| 9. Performing Organization Name and Address<br>(1) Aimone-Martin Associates, LLC<br>1005 Bullock Blvd<br>Socorro, NM 87801<br>(2) Alaska Seismic & Environmental, LLC<br>2554 Engineers Cutoff Rd<br>Juneau, AK 99801<br>Thru CH2M HILL, 9191 South Jamaica Street, Englewood, CO 80112 | | 10. Work Unit No. (TRAIS) |
| | | 11. Contract or Grant No.<br>DTFH68-09-D-00002 T-13-053 |
| 12. Sponsoring Agency Name and Address<br>Federal Highway Administration<br>Central Federal Lands Highway Division<br>12300 W. Dakota Avenue, Suite 210<br>Lakewood, CO 80228 | | 13. Type of Report and Period Covered<br>Final Report,<br>August 2013 |
| | | 14. Sponsoring Agency Code<br>HFTS-16.4 |

15. Supplementary Notes

COR: Roger Surdahl, FHWA-CFLHD. Review Panel Members: Matt DeMarco and Jeff Berna, FHWA-RC. This project was funded under the FHWA Federal Lands Highway Geotechnical Discipline Program.

16. Abstract

This White Paper addresses the generation and transmission of blast energy and the effects that overpressures and vibrations can have on fish and fish habitat. Management challenges that arise when planning and executing blasting projects are discussed. Scientific studies correlating blasting with impacts to fish and recommended guidelines that limit vibrations, overpressures, and sound pressure levels were reviewed. An overview of mitigation techniques and examples of successful projects are presented.

This White Paper draws conclusions that standardized methods are needed for the metrics and measurement systems that explain fish damage, the blasting effects on fish, mitigation, and project planning. Recommendations of areas where further work is needed include metrics in terms of pressure to predict the effects on fish with distance, distinguish between blasting and non-blasting activities, effects of blast overpressures, and identifying what pressure and vibration levels and parameters of blast strength cause injury and mortality in fish.

| | |
|---|---|
| 17. Key Words<br>**BLAST-INDUCED VIBRATION, FISH, FISH HABITAT, FISH INJURY, OVERPRESSURE, SOUND EXPOSURE LEVEL, SOUND PRESSURE** | 18. Distribution Statement<br>No restriction. This document is available to the public from the sponsoring agency at the website http://www.cflhd.gov. |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price |
|---|---|---|---|
| Unclassified | Unclassified | 95 | |

**Form DOT F 1700.7 (8-72)** **Reproduction of completed page authorized**

# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yard | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| | | NOTE: volumes greater than 1000 L shall be shown in $m^3$ | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact degrees)** | | |
| °F | Fahrenheit | 5 (F-32)/9 or (F-32)/1.8 | Celsius | °C |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/$in^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |

## APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.314 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact degrees)** | | |
| °C | Celsius | 1.8C+32 | Fahrenheit | °F |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003

# TABLE OF CONTENTS

**CHAPTER 1 – INTRODUCTION ..... 1**

**CHAPTER 2 - GENERATION, PROPAGATION AND MEASUREMENT OF BLAST WAVES ..... 3**

- 2.1 Ground Vibrations ..... 3
  - 2.1.1 Characteristics and measurements ..... 3
  - 2.1.2 Comparison of vibration time histories ..... 5
  - 2.1.3 Frequency content and predominant frequency ..... 11
  - 2.1.4 Attenuation of non-blasting construction ground vibrations ..... 12
- 2.2 Water Overpressures ..... 13
  - 2.2.1 Characteristics and measurements for blasting and blast hole drilling ..... 13
  - 2.2.2 Comparison of time histories ..... 14
  - 2.2.3 Metrics used to assessment underwater blasting impacts on aquatic environments ..... 17
  - 2.2.4 Frequency content ..... 25
  - 2.2.5 Attenuation of blast overpressures ..... 28
  - 2.2.6 Concluding comments on water overpressure metrics applied to blasting ..... 29

**CHAPTER 3 – AVAILABLE MONITORING EQUIPMENT AND MEASUREMENT STANDARDS ..... 31**

- 3.1 Vibration and airblast equipment and measurement standards ..... 31
  - 3.1.1 Geophones ..... 31
  - 3.1.2 Geophone sampling positions ..... 31
  - 3.1.3 Geophone sampling rates ..... 31
  - 3.1.4 Seismograph calibration ..... 31
- 3.2 Water overpressure equipment and measurement standards ..... 32
  - 3.2.1 Hydrophones ..... 32
  - 3.2.2 Hydrophone sampling positions ..... 32
  - 3.2.3 Hydrophone sampling rates ..... 33
  - 3.2.4 Hydrophone calibration ..... 33

**CHAPTER 4 - ADVERSE EFFECTS ON FISH FROM BLASTING AND CONSTRUCTION ACTIVITIES VIBRATION ..... 35**

- 4.1 Factors influencing fish response to overpressures ..... 35
- 4.2 Overpressure effects on fish with emphasis on blasting ..... 35
  - 4.2.1 Classification of injuries ..... 36
  - 4.2.2 Comparisons of caged fish blasting studies on salmonids ..... 37
- 4.3 Mechanical shock – vibration effects on embryos ..... 38

**CHAPTER 5 - DISCUSSION OF METRICS TO DESCRIBE BLAST OVERPRESSURES ..... 41**

**CHAPTER 6 - MITIGATION MEASURES ..... 43**
6.1 Work window timing restrictions ..... 43
6.2 Fish removal ..... 43
6.3 Diversions of rivers and streams ..... 43
6.4 Scare charges ..... 43
6.5 Bubble curtains and barriers ..... 44
6.6 Visual monitoring with a pre-defined safety zone ..... 44
6.7 Modifications to pile driving methods ..... 44
6.8 Blast design modifications to comply with performance specifications ..... 45

**CHAPTER 7 - APPLICABLE CRITERIA ..... 47**
7.1 Ground vibration and overpressure criterion for blasting ..... 47
7.2 Pile driving criteria: fisheries hydroacoustic working group ..... 47

**CHAPTER 8 - PROJECT PLANNING, PERMITTING, AND MANAGEMENT ..... 49**
8.1 Regulatory permitting requirements ..... 49
8.2 State resource agency requirements ..... 50
8.2.1 California ..... 50
8.2.2 Oregon ..... 50
8.2.3 Washington ..... 50
8.2.4 Alaska ..... 51
8.2.5 Canada Department of Fisheries and Oceans ..... 51
8.3 Pre-construction plans and submittals for blasting ..... 52
8.3.1 Blasting plans ..... 52
8.3.2 Monitoring plan ..... 53
8.3.3 Community relations plans and outreach education programs ..... 54
8.4 Project implementation: best management practices (BMPs) ..... 54
8.4.1 The use of consultants ..... 56
8.4.2 Managing permit conditions ..... 57

**CHAPTER 9 - EXAMPLES OF AQUATIC BLASTING PROJECT SPECIFICATIONS 59**

**CHAPTER 10 - CONCLUSIONS AND RECOMMENDATIONS ..... 61**
10.1 Conclusions ..... 61
10.1.1 Metrics and measurement systems used to explain fish damage ..... 61
10.1.2 Blasting effects on fish ..... 61
10.1.3 Mitigation ..... 62
10.1.4 Project planning ..... 62
10.2 recommendations ..... 63

**REFERENCES ..... 65**

**APPENDIX A – SCOPING DOCUMENT SUBMITTED BY CENTRAL FEDERAL LANDS HIGHWAY DIVISION, FEDERAL HIGHWAY ADMINISTRATION (FHWA) 71**

**APPENDIX B – EXAMPLES OF STATE RESOURCE AGENCY PERMITS FOR BLASTING ........ 78**

California ........ 78
Oregon ........ 79
Washington ........ 81
Alaska ........ 82

**APPENDIX C – EXAMPLES OF PROJECT IN WHICH BLASTING IS THE BEST ALTERNATIVE ........ 84**

USFS, Duffield and Fish Bay Fish Passage and Habitat Improvement Projects ........ 84
USFS, Fish Habitat Enhancement Projects ........ 84
US Army Corps, Columbia River Channel Improvements ........ 85

## LIST OF FIGURES

**Figure 1**. Schematic of a tri-axial ground motion geophone housing three velocity transducers.. 4

**Figure 2**. Vibration time histories showing time duration and the peak particle velocity (PPV) (a), the calculation of frequency (b), and uniform frequency content (c). 4

**Figure 3**. Single production blast hole time history for a close-in signature (single) hole used to characterize fundamental rock frequency; V component peak is 2.4 in/s. 6

**Figure 4**. Example of ground vibration time histories for construction blasting using time-delayed multiple blast holes; peak velocities are 0.18 and 0.22 in/s in the V and R components, and 6

**Figure 5**. Comparison of ground vibrations during a shallow underwater blast, measured on land adjacent to the stream and measured at the base of gravel substrate; geophoneswere 69 ft from the blast. 7

**Figure 6**. Examples of ground vibration time histories for construction equipment. 8

**Figure 7.** Fast Fourier Transformations (FFT) of ground motions show the distribution of frequency content and predominance of frequency (the y-axis is measured as relative amplitude or energy). 12

**Figure 8**. Generalized attenuation of peak velocities with distance for rock blasting in comparison with 13

**Figure 9**. Example of a pressure-time recording of a single detonation 50 ft from a blasting cap in open 14

**Figure 10**. Production blast pressure-time history for well-coupled, buried explosive charges drilled into the bottom of a river with a 40 ft column of water measured 140 ft away. 14

**Figure 11**. Pressure-time histories for a blast drilled into the bottom of a shallow river measured at two distances; 6.6 psi peak pressure and 595 Hz peak frequency measured at 15 ft (a) and 1.3 psi peak pressure and 714 Hz peak frequency measured at 42 ft away from the blast (b). 15

**Figure 12**. Pressure-time history for a land-based blast transmitted at the rock/water interface into a stream 40 ft from the hydrophone placed 10 ft from the water surface; stream depth 15 ft. 15

**Figure 13.** Peak overpressure of 0.28 psi during underwater drilling 5 ft from the source. 16

**Figure 14**. Pile driving impulses over 6 second measurement window (a) and single noise impulse from one pile strike (b). 17

**Figure 15**. Pressure-time history shown in Figure 9 for a single blasting cap showing the peak pressure ($P_{pk}$) equal to the positive peak $P_1$, peak negative pulse, $P_2$, and peak bubble phase, $P_b$. $P_0$ is the background noise associated with the river velocity. 19

**Figure 16.** Initial instantaneous positive impulse used to demonstrate peak-to-peak pressure (a) and time interval used to calculate first positive impulse (b) 19

**Figure 17**. Pressure versus time for an underwater production blast of a rock ledge at the rock/shore interface of a reservoir measured at 90 ft from the blast. 22

**Figure 18**. Peak sound pressure computed from the maximum absolute value of instantaneous sound pressure that occurred over a 0.2 second time window. .................................................... 22

**Figure 19**. Root mean square (RMS) "equivalent" pressure for the 0.2 s window shown in Figure 18........................................................................................................................... 23

**Figure 20**. "Effective" sound pressure level is computed for the time history containing .......... 24

**Figure 21**. Examples of typical frequency content analysis for underwater sound in terms of sound pressure (upper right hand plot) (a) and in term of sound exposure using 1/3 octave bandwidths (b). ........................................................................................................... 27

**Figure 22**. Example of water overpressure scaled distance attenuation using hydrophones placed at varying distances away from underwater production blasts using varying quantities of explosive charge weights per delay. ....................................................................................... 29

**Figure 23**. Reported blast peak overpressures for caged salmonid studies. The dashed line (10.0 psi) indicates the lowest peak overpressure where salmonid injury was documented (Godard et 38

**Figure 24**. Reported PPVs salmonid embryos were exposed to in mechanical shock tests. Dashed line (5.8 in/s) indicates the lowest measured PPV that caused mortality (Jensen 2003). Values with asterisk (*) indicate reported exposures that did not cause mortality. LT = lake trout, RT = rainbow trout. ........................................................................................................... 40

# LIST OF TABLES

**Table 1**. Pile driving studies demonstrating thresholds to damage during pile driving and recommended threshold. .......... 48

**Table 2**. Marine blasting project specifications for overpressure monitoring. Maximum allowable overpressures (psi) and monitoring locations are listed for three projects. .......... 60

# CHAPTER 1 – INTRODUCTION

The Federal Highway Administration (FHWA) Federal Lands Highway Division engages in the planning, design, construction, and rehabilitation of public roads and bridges that provide access to Federal and Indian lands. Many of the FHWA projects occur in environmentally sensitive areas. Thus, the agency must deliver environmentally sound engineering design and implementation. In many instances projects involve construction techniques that create noise and vibrations considered to be potentially damaging or disrupting to wildlife.

Construction activities generate continuous and single, transient vibrations during the operation of dozers, loaders, compactors, pile drivers, rock hammers, generators, and during rock removal using drilling and blasting methods. Vibration sources can occur in close proximity to important historic structures, land formations, water bodies, or within wilderness areas containing high value habitat and aquatic species protected by many federal and state agencies. As such, the planning of projects involving activities such as pile driving and rock blasting are often subject to delays and various stipulations from other agencies with the goal of protecting sensitive environments and species.

FHWA is dedicated to promoting environmental stewardship with the many federal and state agencies with whom they work to avoid, minimize, or mitigate construction vibration impacts to sensitive areas. With this in mind, the intent of this White Paper is to overview both technical and management issues concerning vibrations generated by construction activities near bodies of water, and provide high-level guidance in the areas of regulatory compliance and mitigation measures that may promote timely resolve to vibration-related concerns. The original scoping document, prepared by FHWA, is given in Appendix A. The document is organized as a series of questions and answers that form the basis of this Paper and should be considered an overview of topics.

For the purposes of this Paper, sources of construction vibrations are discussed in general, but the primary focus are on blasting and potential impacts on fish and fish habitat in freshwater systems. Environmental permitting of in-water pile driving projects was previously reviewed and discussed in detail in a technical guidance manual prepared for the California Department of Transportation (2009). Contained within this manual is the Interagency Agreement in Principal for Interim Criteria for Injury to Fish from Pile Driving Activities (FHWG 2008). The Interagency Agreement sets forth criteria for peak allowable sound levels during pile driving for the protection of fish and is summarized in this Paper.

This Paper addresses the generation and transmission of blast energy and the effects that overpressures and vibrations can have on fish and fish habitat. The current state of practice is summarized, including: examples of agency regulations, permits, and project specifications; current methods of measuring and monitoring impacts; and a description of mitigation techniques. This paper directly addresses some of the difficulties encountered during the planning and execution of blasting projects in or near sensitive fish habitat. Suggested solutions to resolve the issues are provided and areas of further research and standardization of methods are presented. Finally, examples of successful projects are reviewed.

(blank page)

# CHAPTER 2 - GENERATION, PROPAGATION AND MEASUREMENT OF BLAST WAVES

The purpose of this section is to provide the reader with the tools and information necessary to understand how blast energy is transmitted through the ground and water, how it is measured, and criteria used to limit adverse blast effects on fish and fish habitat. The blasting process involves a chemical detonation or the rapid decomposition of chemicals in which energy and heat are released followed by the rapidly expanding decomposition gases. The detonation reaction forms a high-pressure shock wave ahead of the expanding gases. The detonation and gas pressures create a sudden acceleration of the rock mass within the drill holes that induce dynamic stresses in the walls of the drill holes.

An explosive detonation is considered a transient or impulsive energy source in that the amplitude, or intensity, of pressure varies with time over a very short duration. In contrast to continuous or repetitive energy from pile driving, rock hammering, or dredging, blast pressure durations are measured in millisecond (ms). The time-variant contains both positive (compressive) and negative (tensile) pressures. When multiple blast holes are sequentially detonated using time delayed initiators, the cumulative effect is a series of positive and negative peaks over several hundred milliseconds and usually less than one second.

The stress pulsing of the rock creates three types of disturbances, or wave motions, when blasting in and around bodies of water. These include ground vibrations, air overpressure, and water overpressure when blasting on land next to water or under water. When blasting takes place under a deep water column, air overpressure to the atmosphere may be absent due to excessive confinement. During land and underwater blasting, ground vibrations travel along the rock surface and within a water body substrate in the form of particle velocities. Water overpressures can be generated from the pulsing of water when ground vibrations reach a rock-water interface or directly from underwater blasting when the rock is quickly accelerated against the water column. *With respect to rock blasting effects on fish, substrate vibrations and water overpressures are most relevant.*

## 2.1 GROUND VIBRATIONS

### 2.1.1 Characteristics and measurements

Ground particle motions in rock and substrate are characterized in terms of amplitude or intensity, frequency (f, in cycles per second or Hertz, Hz), and duration (seconds, s). The amplitude or intensity of ground vibration is commonly reported as peak particle velocity (PPV, in inches/second, in/s, or millimeters/second, mm/s) and is measured using tri-axial geophones that are well-coupled to the substrate in a water body or in the ground on land adjacent to water. A schematic of a tri-axial transducer is given in Figure 1. PPV is, by definition, the highest amplitude of ground motion over time as measured in any one of the three components (radial or longitudinal, R, L, vertical, V, or transverse, T) of motion as measured by the tri-axial geophone well-coupled to the ground surface. Historically, velocity transducers have been the measurement device of choice based on cost and availability since the 1960’s. Velocity transducers have been used for over 40 years to set limits, correlate measurements with structure damage potential, or to control impacts during blasting and construction when mitigation or modification of methods is important.

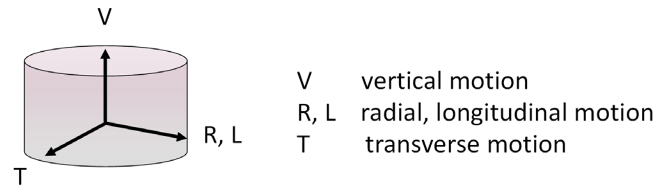



***Figure 1****. Schematic of a tri-axial ground motion geophone housing three velocity transducers.*

Frequency is an important characteristic of vibration waves as it determines how fast an impulse occurs and is related to the total energy that a pulse imparts to the ground or within the water. Ground vibration measure should always include the frequency associated with the PPV. Frequency is computed as the inverse of time over which the PPV occurs between the two "zero-crossings" forming the PPV. A typical blast pulse for one component is shown in Figure 2 and the PPV is identified for the complete time history (a). The expanded portion containing the positive PPV amplitude (b) shows the two locations along the dashed line representing "0" amplitude where the pulse contains the PPV.

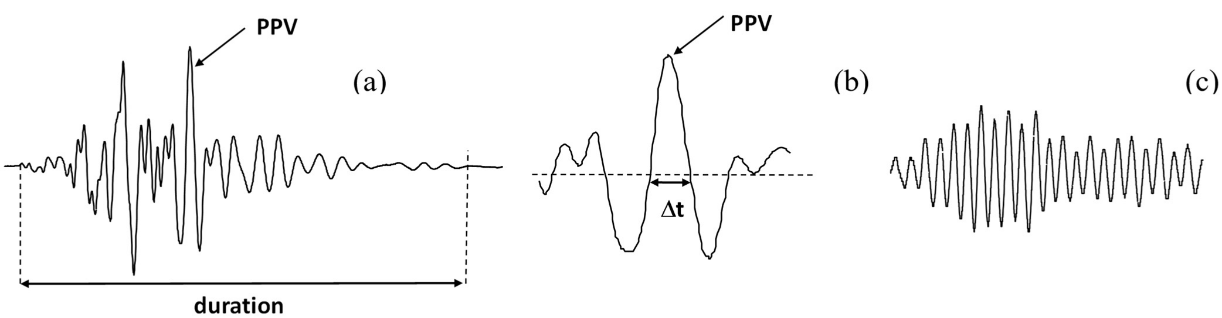



***Figure 2****. Vibration time histories showing time duration and the peak particle velocity (PPV) (a), the calculation of frequency (b), and uniform frequency content (c).*

The time duration ($\Delta t$) of this single half-pulse (or half cycle) containing the PPV is used to compute the peak frequency (or frequency at the PPV) as shown in Equation (1).

$$f = 0.5 \text{ cycles} / \Delta t \text{ second} \qquad (1)$$

In some special cases, the peak ground displacement (D, in inches, in, or millimeters, mm) or peak acceleration (A, in $in/s^2$, g's, or $mm/s^2$) is required for analysis and reporting. Displacement and acceleration time histories are simply the integration and differentiation of the velocity time history, respectively, and the peak over time is reported. Both 'D' and 'A' are highly influenced by the frequency content of the entire velocity pulse and not necessarily just the frequency at the PPV.

In some instances as shown in Figure 2 (c), the time history comprises positive and negative pulse of nearly uniform frequencies where ‘f’ is a constant. In this case, ‘D’ and ‘A’ occur at the PPV and can be approximated using the formulae for a sinusoid as follows:

$$A_{peak} = 2\pi f\,(PPV) \tag{2}$$

$$D_{peak} = (PPV) / 2\pi f \tag{3}$$

Accurate measurement of vibrations requires use of a tri-axial geophone that is well-coupled within the substrate beneath a water body or in the ground adjacent to water bodies. Geophones should be installed according to the International Society of Explosives Engineers (ISEE) Field Practice Guidelines for Blasting Seismographs (2009). Improper coupling of geophones can cause erroneously high measurements if the transducer is not properly weighted or contained within the ground.

Waterproof geophones and cable connections are required when vibrations must be measured in underwater substrates and transducers must be encapsulated with epoxy for protection. Cable connections to the recording seismograph must be watertight to prevent water-induced electronic spikes in the vibration time histories. Other performance specifications for blasting-type seismographs used for general construction vibration measurements can be found in the publication titled ‘Performance Specifications for Blasting Seismographs’ (International Society of Explosives Engineers, 2011).

### 2.1.2 Comparison of vibration time histories

#### *A. Rock blasting vibrations*

Vibration time histories from blasting are characterized based on peak amplitude, peak frequency, and time duration of the pulse. The frequencies associated with blasting typically range from 10 Hz to 100 Hz depending on rock properties such as hardness, mineralogy, degree of weathering, and natural fracturing. In most cases the blast is completed in less than 1 s. As such, blasting is considered to be a one-time event transient or short-term energy source.

Figures 3 and 4 show typical time histories for a single hole, short duration blast and a full-scale production construction blast, respectively. Single hole blasts are often used to characterize rock response prior to blast design. The peak amplitude measured at a distance of 200 ft for the single hole shown in Figure 3 is 2.4 in/s with a peak frequency of 25 Hz. The pulse duration is very short and less than 100 ms or 0.1 s.

The production blast shown in Figure 4 comprises over 80 blast holes, each detonated on a single time delay 8 ms apart. The resulting time history duration measured 1,200 ft from the blast is slightly over 0.7 s. Peak vibration amplitudes are 0.18 and 0.22 in/s for the vertical and radial components with peak frequencies of 57 and 41 Hz, respectively.

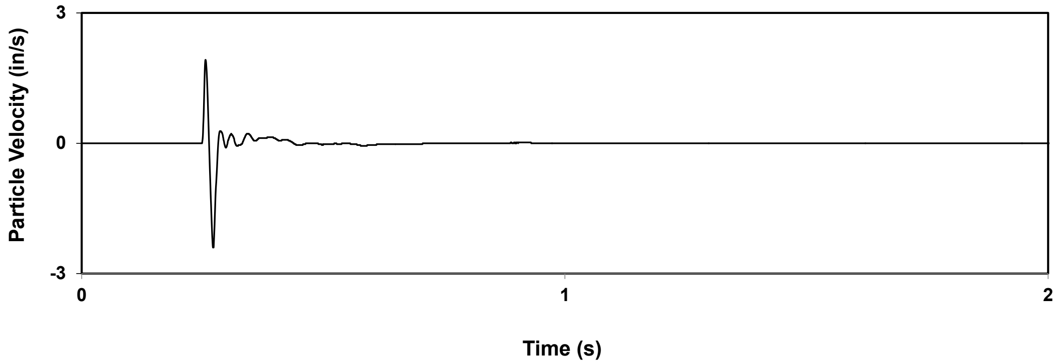



***Figure 3***. *Single production blast hole time history for a close-in signature (single) hole used to characterize fundamental rock frequency; V component peak is 2.4 in/s.*

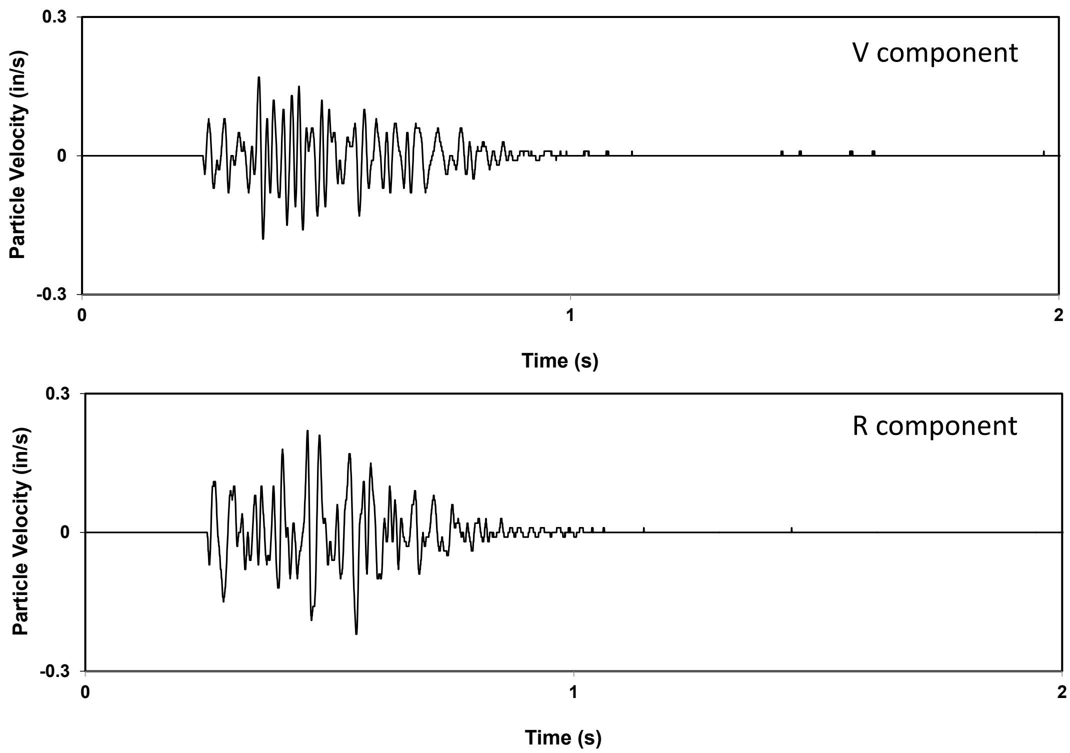



***Figure 4***. *Example of ground vibration time histories for construction blasting using time-delayed multiple blast holes; peak velocities are 0.18 and 0.22 in/s in the V and R components, and 57 and 41 Hz peak frequencies in the V and R components.*

Two vertical component time histories for a small underwater blast in a shallow stream are given in Figure 5 for geophones mounted on the land adjacent to the stream and below the gravel substrate in the stream. Both sensors were 69 ft from the blast. The land peak values were 0.145 in/s velocity and 205 Hz frequency. The substrate values were 0.16 in/s velocity and 171 Hz frequency. High frequencies were typical of hard, saturated rock. The characteristic time histories are nearly identical because both geophones were coupled to rock.

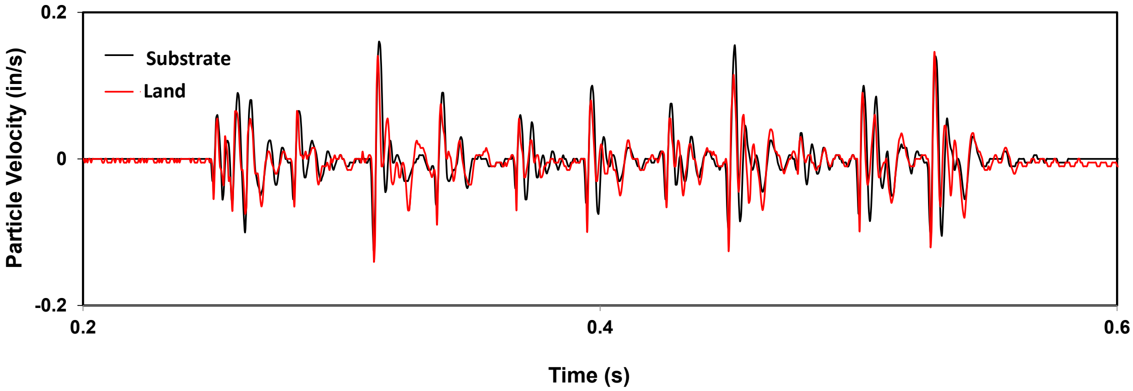


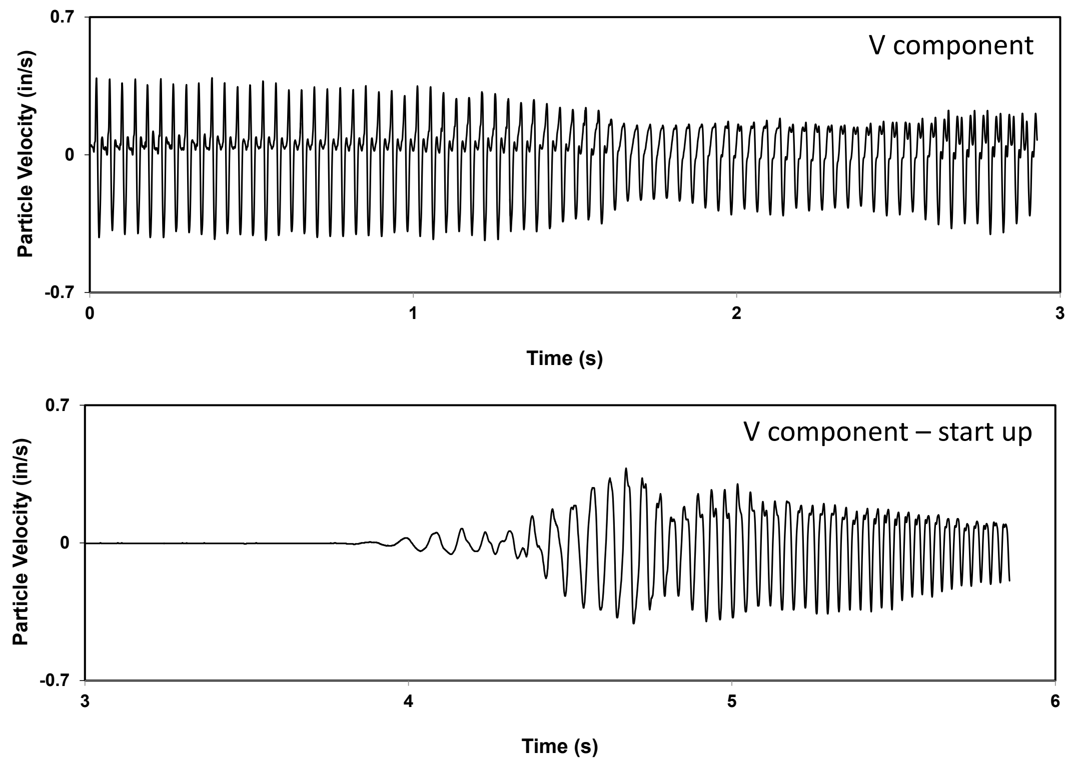

***Figure 5**. Comparison of ground vibrations during a shallow underwater blast, measured on land adjacent to the stream and measured at the base of gravel substrate; geophoneswere 69 ft from the blast.*

### *B. Non-blasting construction vibrations*

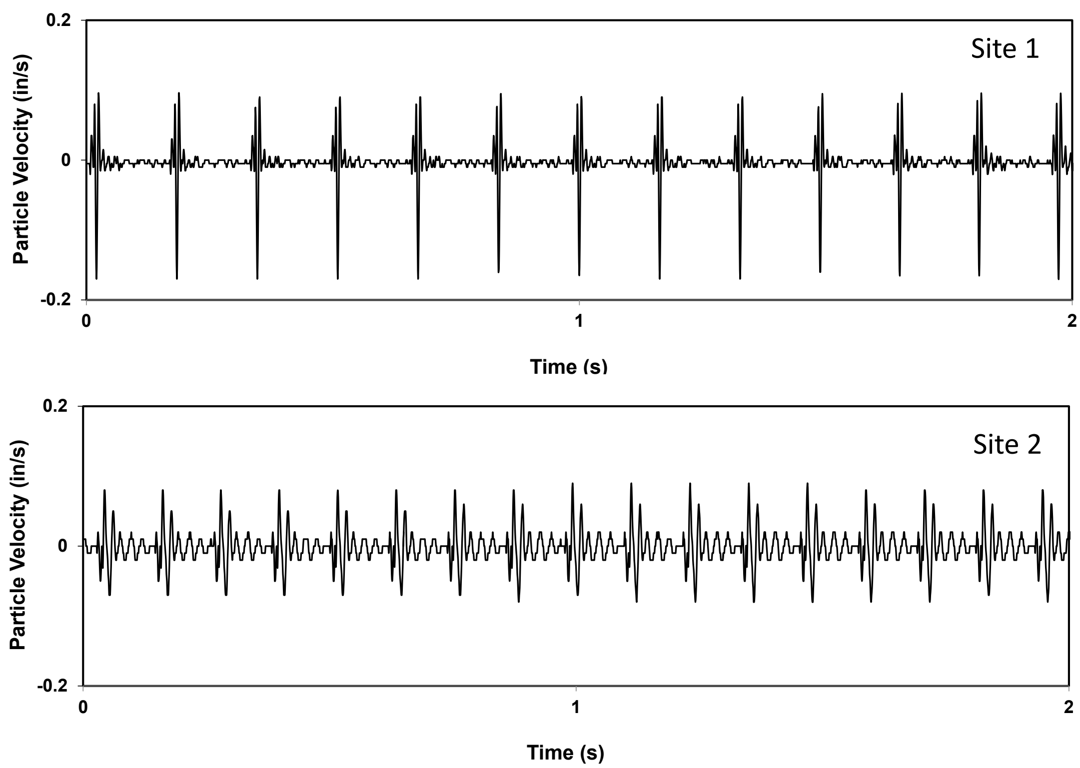
In general, non-blasting construction vibrations can be grouped into several categories of energy transmission that includes impacting (rock hammering and pile driving), vibratory compaction, rotating or grinding (rock trenchers, drilling), scraping (bucket excavators or blades) and rolling (trucks). Examples of vibration time histories during representative equipment operation are given in Figure 6.

In contrast to blasting, construction vibrations are classified as continuous and repetitive over a given time period that may last minutes or hours. Ground vibrations do not dissipate near continuously operating equipment as readily as in the case of blasting. If the vibrational frequency from equipment matches the natural frequency of the ground or nearby structure, the vibration amplitude may amplify within structures and prolong motions in the off-site environment.

Each energy source and piece of equipment creates its own unique vibration time history and frequencies. Impacting energy sources that create the highest initial energy include pile driving and rock hamming. Drilling and trenching time histories carry the highest frequencies, commonly ranging between 70 and 90 Hz. These rotating energy sources use pointed cutting tools that impart high localized energy that decays quickly with distance.

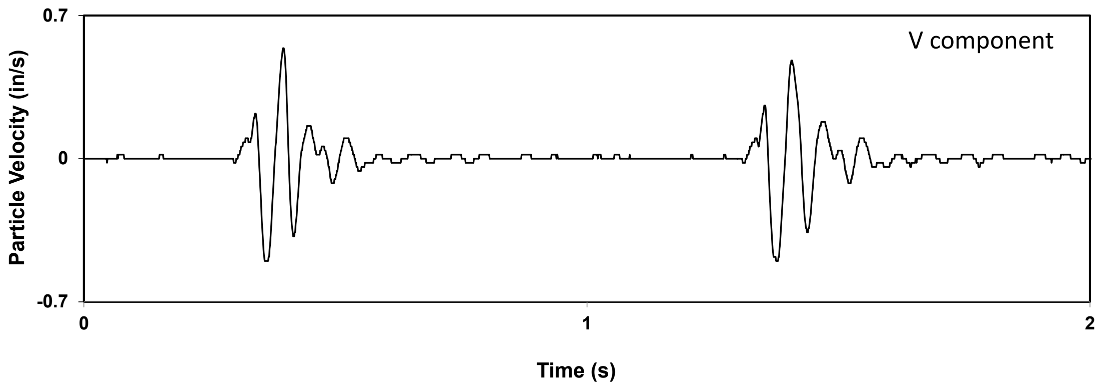



*(a) Vibratory compaction rollers*

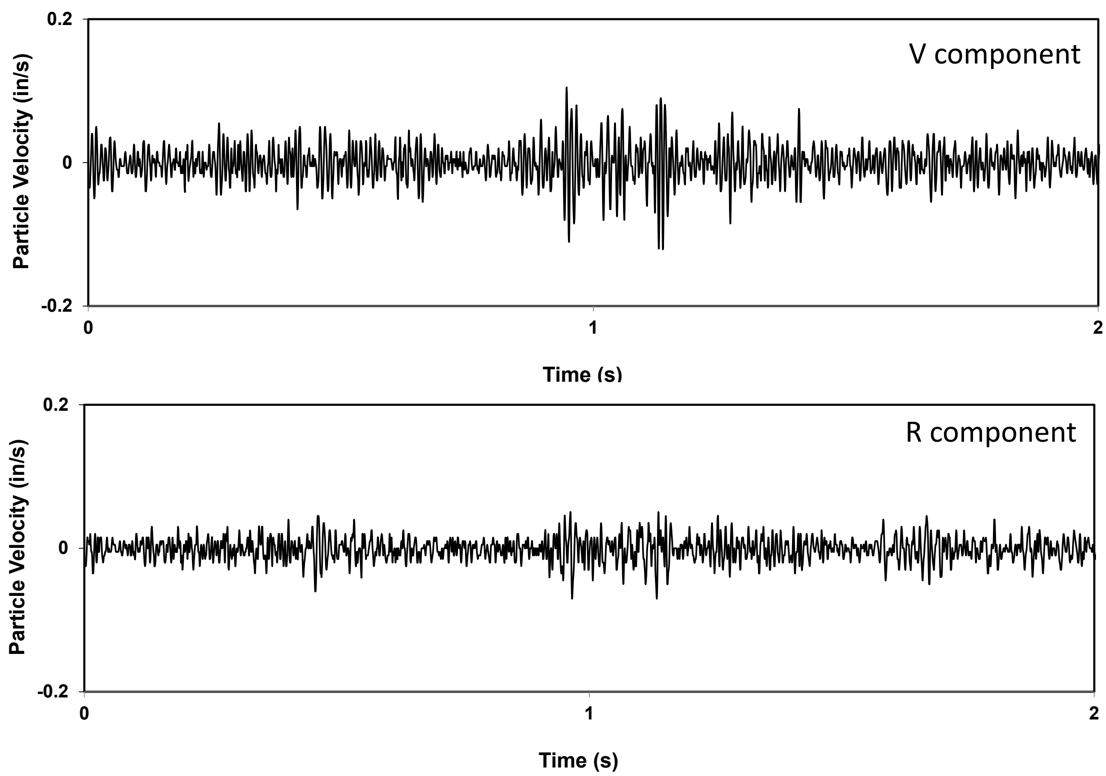



*(b) Rock hammers*

***Figure 6***. *Examples of ground vibration time histories for construction equipment.*

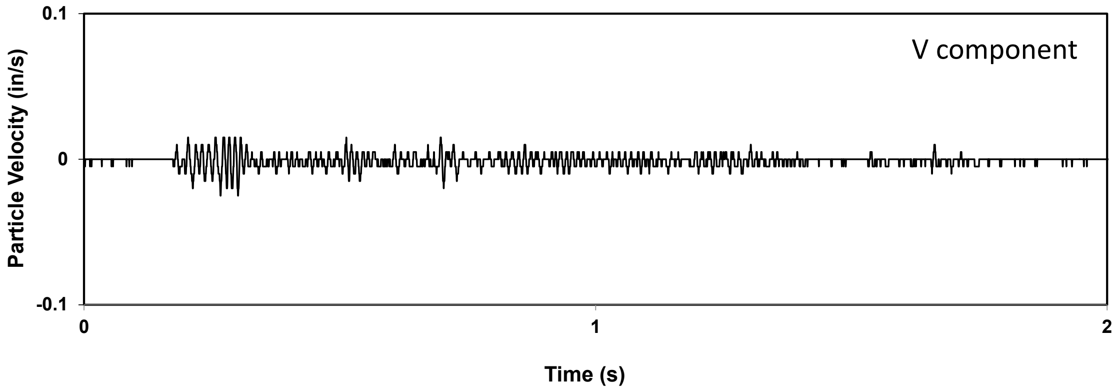



*(c) Impact pile driver*

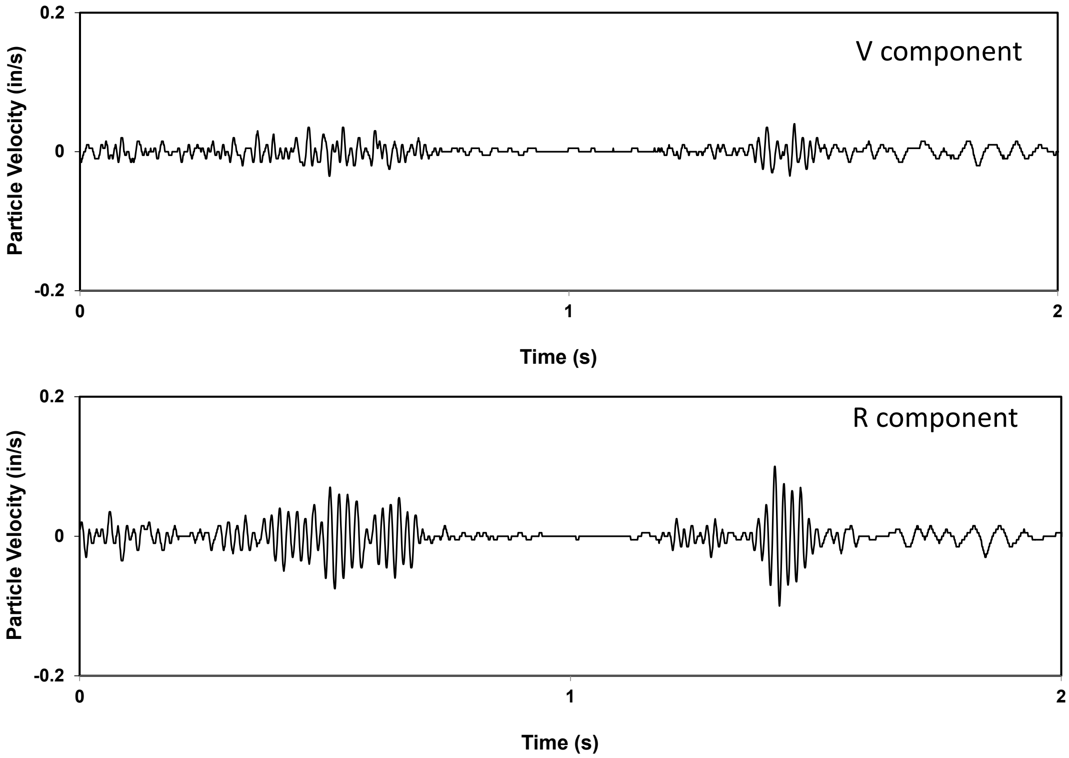



*(d) Rock trencher*

***Figure 6.*** *Examples of ground vibration time histories for construction equipment (cont.)*

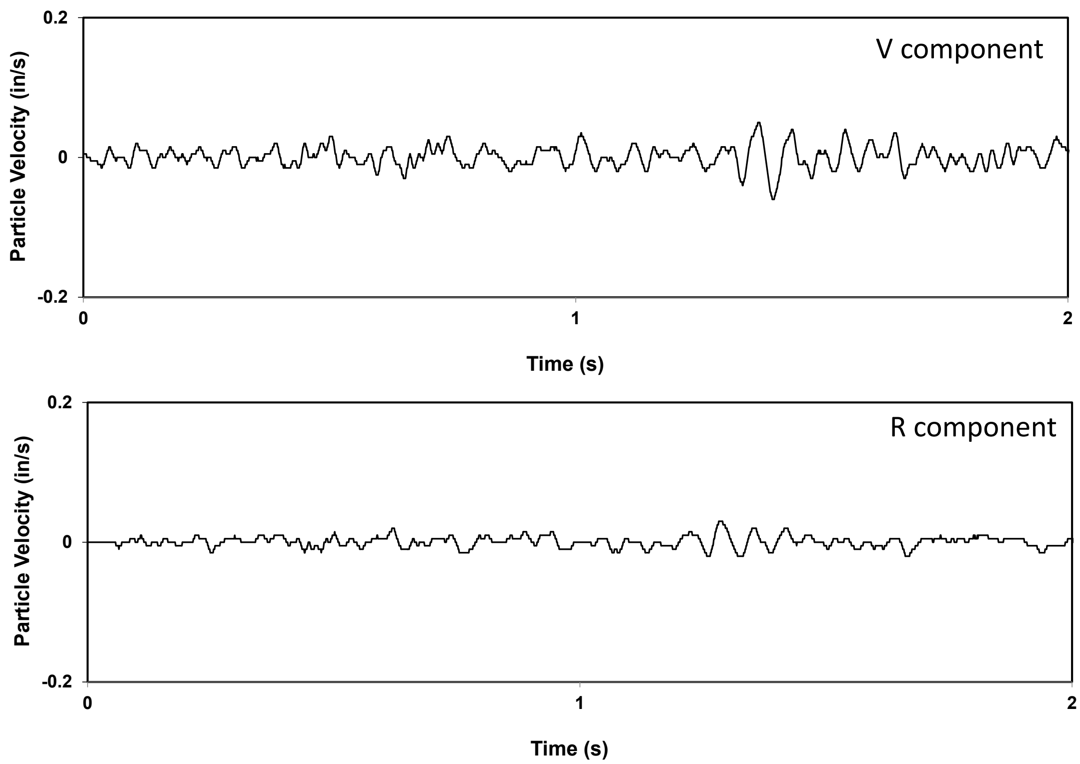



*(e) Rock drilling*




*(f) Excavator bucket against rock*

***Figure 6.*** *Examples of ground vibration time histories for construction equipment (cont.)*




*(g) Scraper blade on irregular rock surface*

***Figure 6.*** *Examples of ground vibration time histories for construction equipment (cont.)*

Dowding (2000) reviewed construction vibrations for various forms of energy transmission and found that expected particle velocities at 32.8 ft (10 m) for most types of equipment ranged from 0.04 to 0.39 in/s (1 and 10 mm/s) and up to 0.59 in/s (15 mm/s) for high impact energy sources (i.e. vibratory compaction rollers and impact pile drivers).

### 2.1.3 Frequency content and predominant frequency

The frequency content of the entire ground vibration time history is often of interest when blasting in the vicinity of above-ground sensitive structures and other features (e.g., modern structures, historic buildings, archeological sites, natural rock features). The distribution of blasting ground motions frequencies can range from 2 Hz to over 300 Hz while the predominant frequencies are often low. Frequency content can become critical when predominant frequencies of ground motions fall near the protected structure's natural or fundamental frequency. This may set a structure in motion resulting in amplification of response vibrations and lengthen the time over which the structure shakes.

Frequency content is analyzed using Fast Fourier Transform (FFT) analysis in which the peak motions are transformed from the time domain to the frequency domain. Simply, each positive or negative peak amplitude is analyzed with respect to the zero-crossing frequency in the time domain. The total ground motion energy contained within narrow bandwidths of frequency analysis (usually 1 Hz bins, such as 1 to 2, 2 to 3, and so forth) are summed and histograms of cumulative energy or power are plotted for each discrete bandwidth. Figure 7 shows two such plots in which the histogram is replaced with a smooth function. The left plot shows a predominance of low frequencies (8 to 20 Hz) with some higher frequency energy above 60 Hz. The right plot has a predominance of 8 Hz, or a nearly constant frequency content.

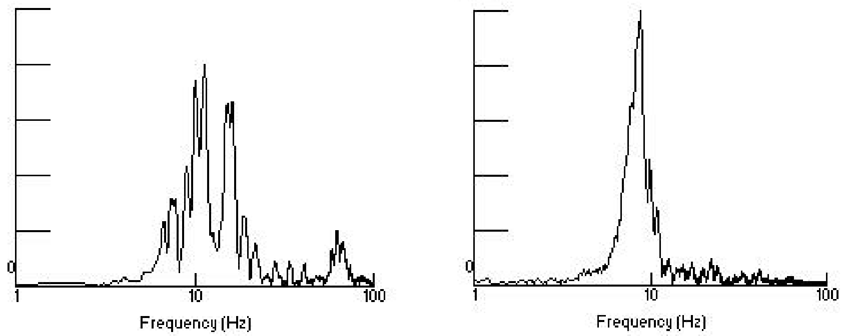



***Figure 7.*** *Fast Fourier Transformations (FFT) of ground motions show the distribution of frequency content and predominance of frequency (the y-axis is measured as relative amplitude or energy).*

### 2.1.4 Attenuation of non-blasting construction ground vibrations

The attenuation or decay of ground motion for various energy sources is generalized in Figure 8. In this plot, distance is not scaled with source energy as is done with explosives. The various colored lines represent ground vibration attenuation slopes in which PPV is correlated with distance. These slopes represent regression best-fit lines computed for vibration measurements from over 500 construction sites throughout the U.S. and include several thousand measurements taken by the authors. Trend lines for various equipment are given either with upper and lower bounds (rock trencher and pile driving) for a wide range of equipment operating conditions or with an average line. These best-fit lines represent a small sampling of trends that can be measured at various sites and for various geologies.

Attenuation plots are developed by using linear arrays of blasting-type seismographs to monitor ground vibrations in terms of PPV away from the energy source. These plots are useful to understand the manner in which equipment operating controls and site geology impact the amplitude of vibrations with distance and often direction. Preparing a site-specific vibration attenuation model can be used as a guide to modify equipment operating energy and frequency in an effort to mitigate and control vibrations with distance. Further, such models may be used in the planning and permitting process to define a "zone of influence" when vibration limits are imposed to protect sensitive environments.

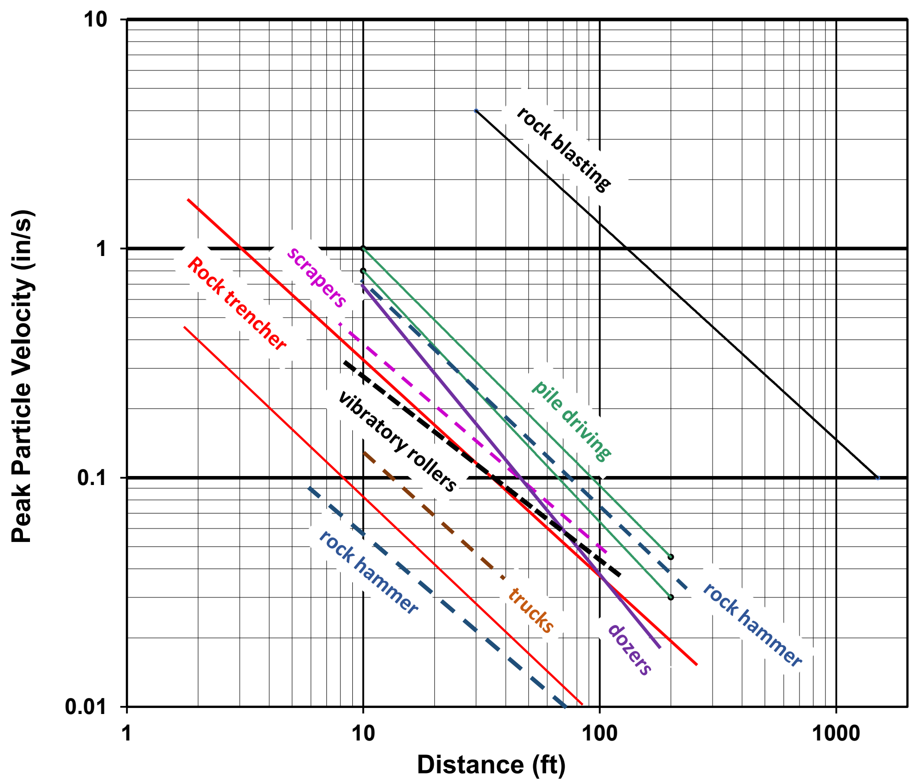



***Figure 8***. *Generalized attenuation of peak velocities with distance for rock blasting in comparison with construction equipment (data are not normalized for source energy).*

## 2.2 WATER OVERPRESSURES

### 2.2.1 Characteristics and measurements for blasting and blast hole drilling

Underwater blast pressures are measured using hydrophones or pressure sensors that record omni-directional pressures from transient pulses in water in units of Pascals (Pa) or pounds per square in (psi). Often time they are referred to as sound waves and contain both compression (positive) and rarefaction (negative) pulsing to the water as they propagate.

Blast-induced water pressures are generally reported as overpressure or pressure in excess of background or ambient pressure. Ambient pressure arises from natural sources such as turbulence, waves, geologic events, rain, and sounds that aquatic organisms produce, and some man-made sources such as boat traffic in a harbor or vessel noise in active shipping channels. The use of explosives adjacent to, within, or beneath water bodies result in a rise in pressure over ambient levels and therefore reported as overpressures.

As with ground vibrations, time histories of measured pressures are characterized by peak values, frequency content, and duration of single events, or peaks can be cumulated over time for single or successive events.

### 2.2.2 Comparison of time histories

#### *A. Rock blasting vibrations*

Examples of blast-induced time histories are given in Figures 9 through 12 for a single detonator, a full-scale production blast in a 40-ft column of water, a small-scale blast in a shallow river, and a controlled blast with pre-split hole 40 ft from the edge of a stream (land blast). Peak overpressures measured several 10's of feet from an underwater blast can reach 200 psi for full-scale blasting and typically average less than 30 psi at distances less than 150 ft away for well-confined charges.

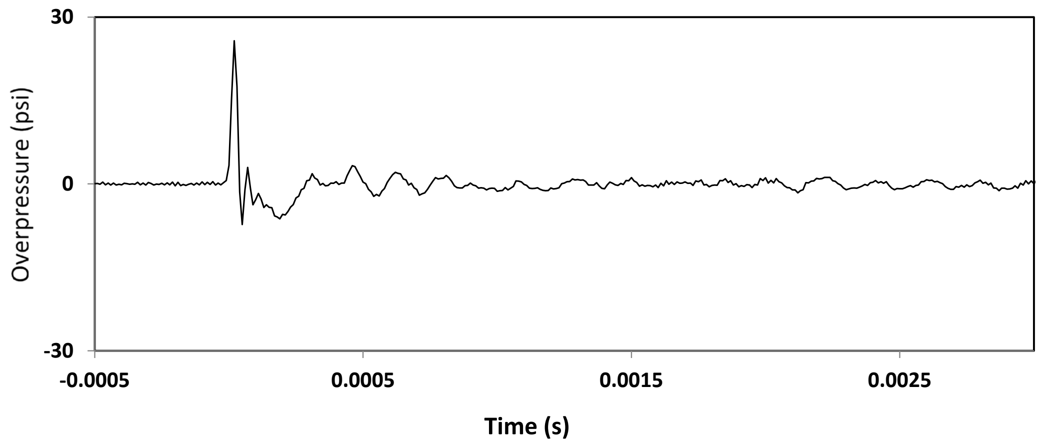



***Figure 9***. *Example of a pressure-time recording of a single detonation 50 ft from a blasting cap in open water; peak pressure is 25.7 psi and peak frequency 8,000 Hz.*

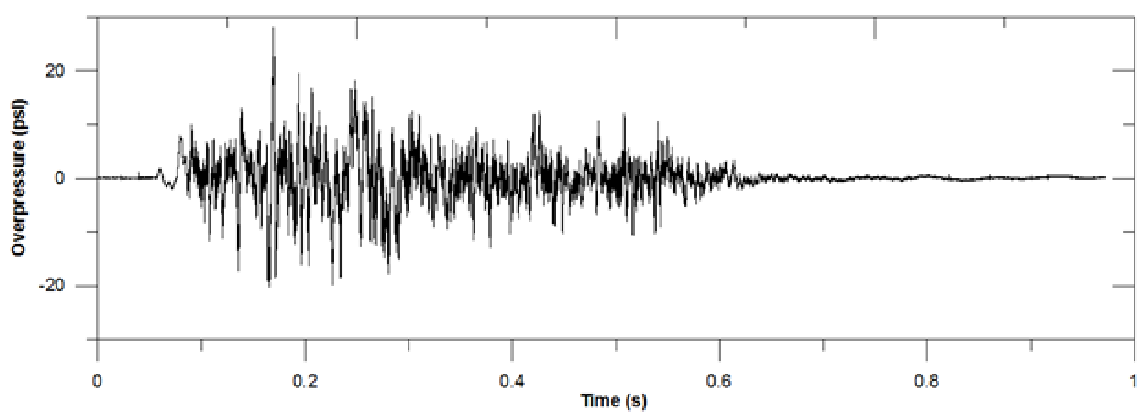
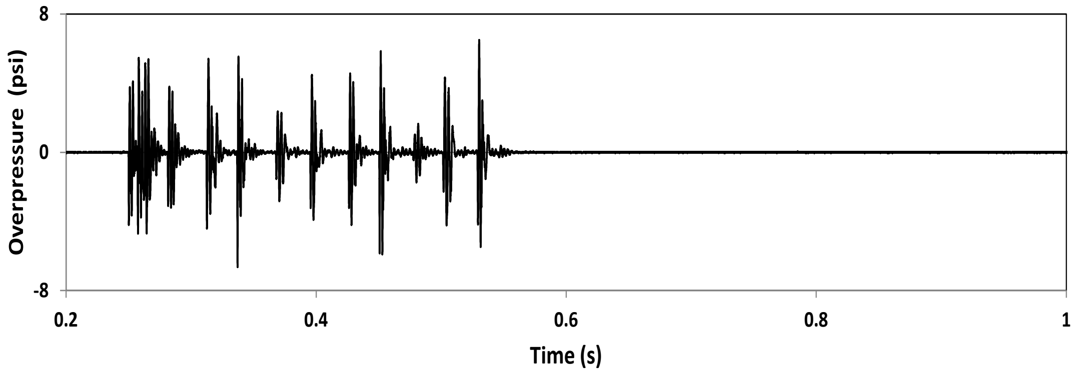



***Figure 10***. *Production blast pressure-time history for well-coupled, buried explosive charges drilled into the bottom of a river with a 40 ft column of water measured 140 ft away.*




*(a)*

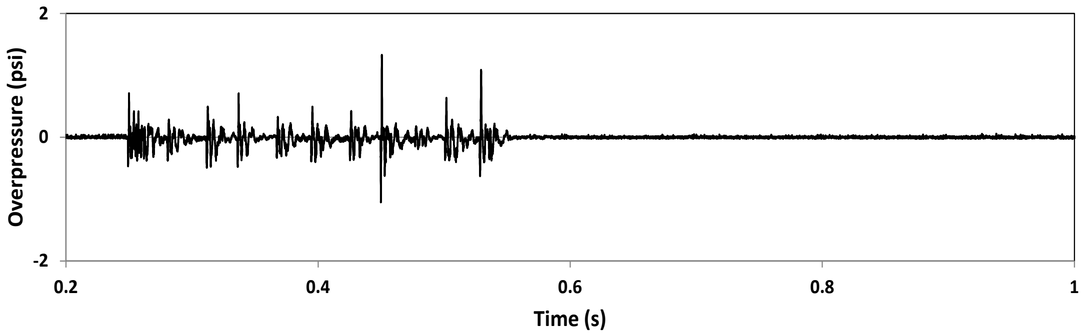



***Figure 11***. *Pressure-time histories for a blast drilled into the bottom of a shallow river measured at two distances; 6.6 psi peak pressure and 595 Hz peak frequency measured at 15 ft (a) and 1.3 psi peak pressure and 714 Hz peak frequency measured at 42 ft away from the blast (b).*

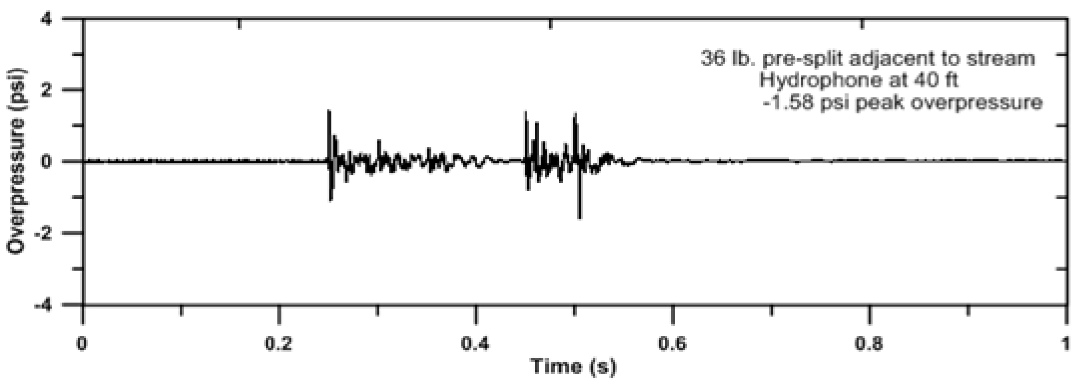



***Figure 12***. *Pressure-time history for a land-based blast transmitted at the rock/water interface into a stream 40 ft from the hydrophone placed 10 ft from the water surface; stream depth 15 ft.*

Blast durations for single charges detonated in the water outside rock, as shown in Figure 9, are extremely short and can result in high frequencies of 8,000 Hz or more because of direct exposure of explosives in the water. The peak overpressure for the production blast shown in Figure 10, with explosive charges well-confined in the rock, is 27.9 psi with a peak frequency of 153 Hz at a distance of 140 ft from the blast. The shallow river blast shown in Figure 11 was conducted from a rock pinnacle whose surface was at water level. This 11-delay blast generated overpressures and frequencies of 6.6 psi and 595 Hz at a distance of 15 ft from the blast and 1.3 psi and 714 Hz at 42 ft away. Time histories from each blast hole, delayed 25 ms apart, can be clearly observed. The high frequencies most likely resulted from lateral rock displacement adjacent to the water. The land-based blast shown in Figure 12 generated a peak overpressure of 1.58 psi and peak frequency of 330 Hz at a distance of 40 ft from the hydrophone in the stream.

In general, there are many factors that contribute to variations in peak frequencies. These factors are related to source (e.g. blast hole) and transmission characteristics. Limited measurements conducted to date suggest that highly confined explosive charges tend to generate lower overpressures. Correlations between blast design and overpressure time history parameters are not possible at this time without further study.

### *B. Rock drilling vibrations*

Overpressures were measured during blast hole drilling by the authors for the shallow river blast. The drill was a small, hand-held Pionjär 120. The pressure sensor was placed 5 ft from the rock-bit interface. Figure 13 shows the overpressure time history and a peak pressure of 0.28 psi. Overpressures generated from mechanical drilling in rock are insignificant when compared with rock blasting.

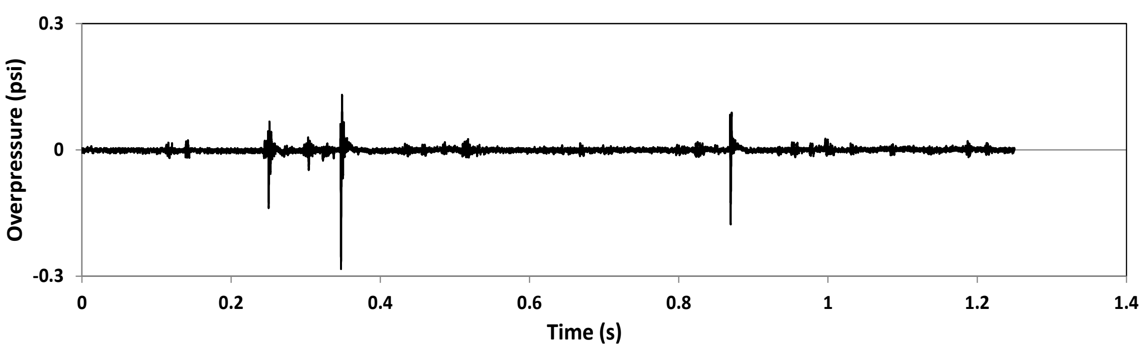
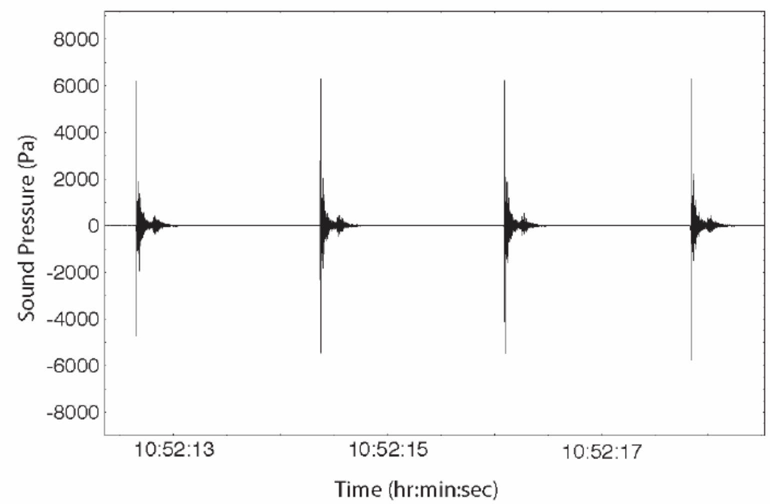


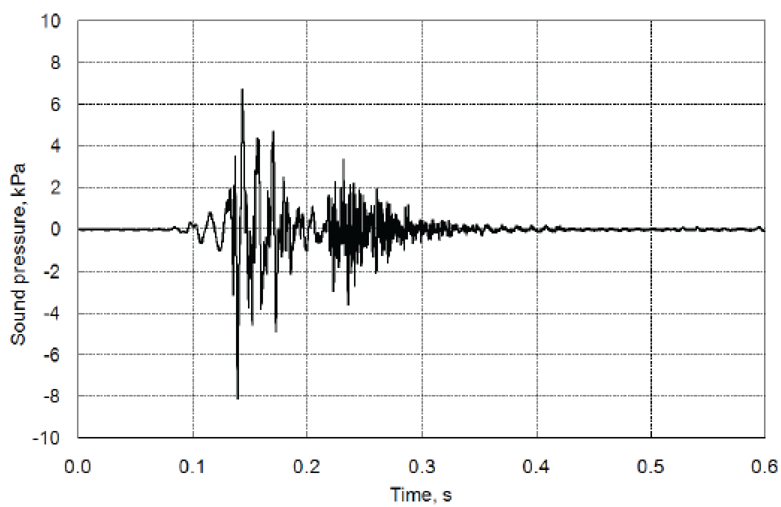

***Figure 13.*** *Peak overpressure of 0.28 psi during underwater drilling 5 ft from the source.*

### *C. Non-blasting construction vibrations*

Examples of continuous non-blasting construction vibrations generated underwater are represented by pile driving time histories shown in Figure 14. These figures were obtained from publications and are plotted in terms of sound pressure in pressure units.




(a) (after Knick Arm Bridge and Toll Authority, 2006)




(b) (after Matuschek and Betke, 2009)

***Figure 14***. *Pile driving impulses over 6 second measurement window (a) and single noise impulse from one pile strike (b).*

The transient nature of pile driving and the time delay between strikes attenuate overpressures to background levels between strikes. When a single strike is expanded in time as in Figure 14 b the characteristic time history appears similar to that of a single blast.

### 2.2.3 Metrics used to assessment underwater blasting impacts on aquatic environments

The metrics used to measure and report underwater blast effects on aquatic species vary widely and, as a result, can cause a great deal of confusion and misunderstanding. The limits placed on blasting are either specified in terms of pressure or in terms of sound pressure in which pressure is converted to sound using a simple log-transformation such that the units are given in terms of decibels (dB).

The application of underwater sound, or hydroacoustics, is used in exploration, navigation, sonar, military warfare, communications, and in oceanographic and environmental studies. In many applications sound pressures can be harmful to aquatic species and limits are often imposed for the hearing protection and behavioral changes (disorientation, change in swim patterns, etc.) of fish and marine mammals. The majority of early research has been directed to defining hearing thresholds and injury to auditory systems of marine mammals. More recent work has focused on measurement descriptors for sound pressure based on intensity and duration of the blast impulse source as it pertains to injury and mortality of fish in general. The same principals used to describe hearing injury are often applied to tissue injury and mortality.

Underwater detonation of an unconfined blasting cap (explosive charge weight measured in milligrams) creates a short duration, high intensity pressure pulse followed by gas bubble expansion pulse as shown in the pressure time history of Figure 15. This type of transient impulse, or one-time event, creates a seismic wave in water far different than a continuous energy source would create that is typical of construction equipment. *Many of the signal processing algorithms used to quantify and mitigate noise exposure for continuous sources such as pile driving, rock hammering, and so forth, cannot necessarily be applied to blasting.* This has led to much confusion and misunderstanding on the part of federal and state agencies when applying limits to blasting when signal processing algorithms derived for continuous noise is applied to blasting transients.

### *A. Metrics based on pressure*

The most common measurement metrics for pressure waves, reported in pounds per square inch (psi) or Pascals (Pa), are as follows:

*Peak Pressure ($P_{pk}$)*

The Peak Pressure *($P_{pk}$)* is the highest pressure attained, either positive or negative, by a sound pressure signal given as $P_1$ in Figures 15 and 16(a). Figure 15 was previously shown in Figure 9. $P_1$ is measured with respect to ambient pressure, and is also referred to as zero-to-peak pressure.

*Peak-to-Peak Pressure ($P_{pk-pk}$)*

Peak-to-Peak Pressure *($P_{pk-pk}$)* is the difference between the highest pressure and lowest pressure over the duration of a waveform, calculated as $P_1 – P_2$ in Figure 15 and shown in Figure 16(a) as 25.7 - (-7.3) or 33 psi. For impulsive sounds produced by blasting, the lowest pressure is generally negative with respect to ambient pressure and occurs soon after the largest positive peak due to expansion imparted to the water by its positive impulse. For complex time histories, the peak positive and peak negative overpressure do not always occur in the same cycle (or sine wave) as shown in Figure 16(a) and measurements are often reported for the difference between peak values regardless where they fall in the time history. Reported measurements often fail to define what peaks are used to compute $P_{pk-pk}$.

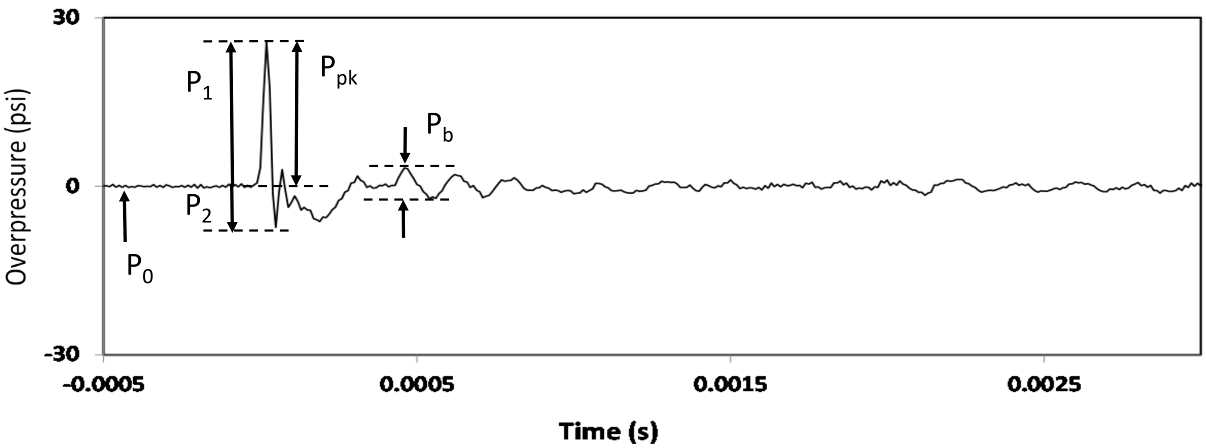



***Figure 15**. Pressure-time history shown in Figure 9 for a single blasting cap showing the peak pressure ($P_{pk}$) equal to the positive peak $P_1$, peak negative pulse, $P_2$, and peak bubble phase, $P_b$. $P_0$ is the background noise associated with the river velocity.*

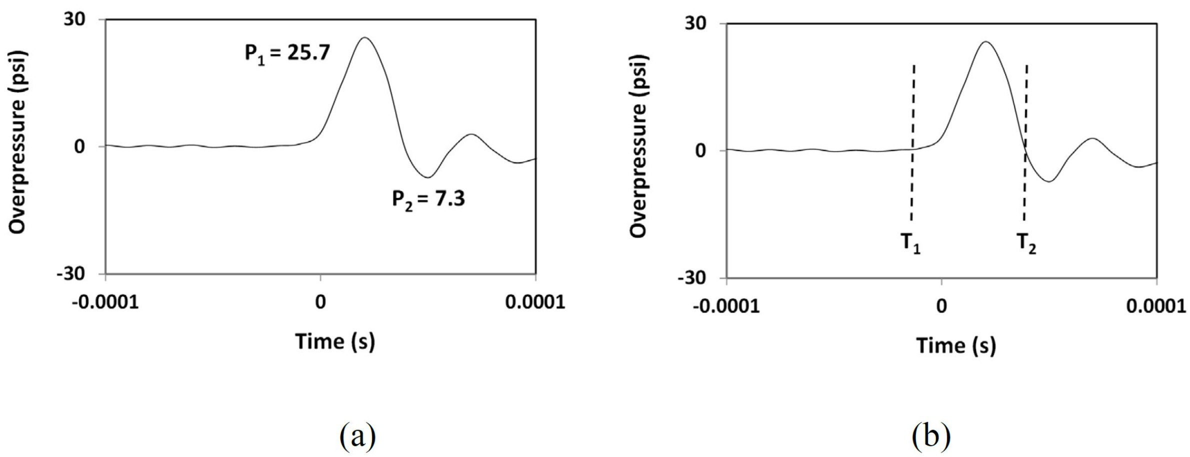



***Figure 16.** Initial instantaneous positive impulse used to demonstrate peak-to-peak pressure (a) and time interval used to calculate first positive impulse (b)*

It is not possible to establish correlations between blast design and overpressures without a clear definition of peak pressure. Regulations and specifications that limit overpressures must clearly define how peak overpressures are calculated. As such, it is difficult to apply mitigating measures to ensure overpressures remain within allowable levels without this definition.

*Impulse (I)*

Impulse (*I*) is defined as the integral of pressure over time and is given by the equation:

$$I = \int_{T1}^{T2} P(t)dt \tag{4}$$

where *I* is the impulse in Pascal-seconds (Pa·s) or psi·s and P(t) is the acoustic pressure of the blast wave over a user-specified time $T_1$ to $T_2$. There is no decibel analog for impulse. As an illustration, the single waveform for a blasting cap detonation is used to compute the positive impulse. Figure

16(b) illustrates the integration interval selected over the initial instantaneous positive peak between the zero crossings at -0.0003 s and 0.0004 s. The resulting impulse is 0.0121 psi·s.

Impulse can be thought of as the energy of the pressure wave over a specified duration. Various time intervals are selected to calculate impulse, such as the interval containing only a single peak, either the positive or negative phase, computing an average pressure over the entire time history, or 95% of the signal for continuous energy sources. However, there is no consistent time period over which impulse is computed. Generally the entire wave pulse is selected or, in some cases, only the duration of the initial positive pressure pulse (positive impulse) is selected. In some cases the average of positive and negative peaks is used for computation. The longer the time interval selected for calculation, the higher the impulse. Therefore the shape of the pressure time history over any specified time interval will have a great influence on the reported impulse.

Impulse is used by some researchers to evaluate the effects of blast pressure on fish. Regardless of the method used to calculate impulse, successive positive and negative peaks must cross the zero pressure time axis. However, pressure pulses from multi-hole blasts and impact pile driving do not always contain such simplified waveforms. Complex time histories may contain oscillations that do not always cross the zero pressure axis and complicate impulse computations. Without a single method, impulse cannot be compared between studies or correlated with impacts to fish. Thus applying operational controls on equipment and blast design are meaningless.

*Energy Flux Density (EFD)*

Energy Flux Density (EFD) is the total acoustic energy propagated through a unit area perpendicular to the direction of propagation. The EFD of plane waves can be computed as the time integral of squared pressure, divided by the acoustic impedance of the medium,

$$EFD = \frac{1}{\rho c}\int_0^{\tau} P^2 \mathrm{dt} \tag{5}$$

where acoustic impedance of water is density, ρ, multiplied by c, the speed of sound in water, and EFD is report in Joules/$m^2$. The integration interval, τ, is a function of a time constant, θ, over which a pressure-time history can be approximated with an exponential decay and before the pressure decline becomes linear. Swisdak et al. (1978) notes that the integration period, τ, should be approximately 5·θ whereas Cole (1948) states the interval should be 6.7·θ.

EFD is referred to as the acoustic impulse noise energy and includes the complete acoustic pressure history. Wartzok et al. (2005) noted if noise exposure is below some critical energy flux density limit, there will be a temporary loss of hearing in marine mammals. Baxter et al. (1982) used energy flux density to predict fish mortality based on weight. However, Govoni et al. (2008) determined specific impulse was the critical parameter for injury assessment to larvae and small juveniles when compared with peak pressure or energy flux density.

In general, EFD may have limited application in underwater blasting due to the complicated pulse shapes and wide range of frequencies that result from multi-hole, time delayed production blasting as shown in Figure 10.

### *B. Metrics based on sound pressure*

In terms of sound, pressure is converted to sound pressure on a decibel (dB) scale which is a logarithmic index based on a ratio between measured pressure and a reference pressure. Using a decibel scale compresses the range of pressures. Figure 17 shows a blast pressure wave plotted in terms of Pascals used to illustrate the metrics defined in this section. Three common sound pressure levels are computed as the absolute peak, peak to peak, and root mean square peak.

*Peak sound pressure level ($SPL_{pk}$)*

Peak sound pressure is based on the absolute peak of the instantaneous sound pressure ($P_{max}$) relative to a fixed reference pressure ($P_{ref}$), given by the following:

$$SPL_{pk} = 20\ log_{10}\ \frac{P_{max}}{P_{ref}} \tag{6}$$

where the reference pressure for water is 1 micro-Pascal (re 1 μPa). Computationally it is simplified to:

$$SPL_{pk} = 20\ log_{10}(\max[P(t)])\ \text{dB re 1 μPa} \tag{7}$$

where maximum P is taken as the absolute value for either the peak positive or negative pressure value over the entire time history. Note that the denominator $P_{ref}$ does not appear in the equation but the addition of dB re 1 μPa behind the equation implies that this term is used to normalize pressure in water. **Note: all underwater sound level calculations in this paper in dB are referenced to 1 μPa.**

In Figure 17, the absolute value of peak pressure, $P_{pk}$, is 26.3 psi or 181,332 Pa (18.133 ($10^{10}$) micro-Pascal). The $SPL_{pk}$ then becomes 225 dB re one micro-Pascal.

*Peak-to-peak sound pressure level ($SPL_{pk\text{-}pk}$)*

The peak-to-peak sound pressure level is given by:

$$SPL_{pk-pk} = 20\ log_{10}(\max[P(t) - \min[P(t)])\ \text{dB re 1 μPa} \tag{8}$$

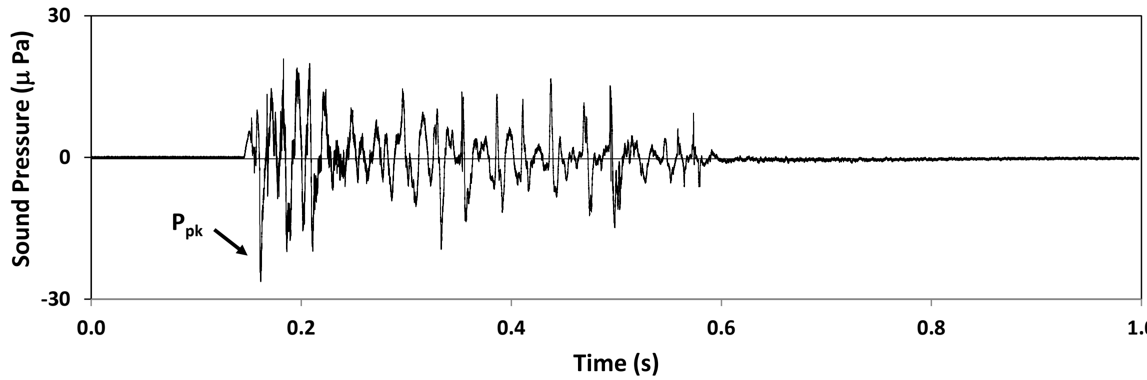



***Figure 17***. *Pressure versus time for an underwater production blast of a rock ledge at the rock/shore interface of a reservoir measured at 90 ft from the blast.*

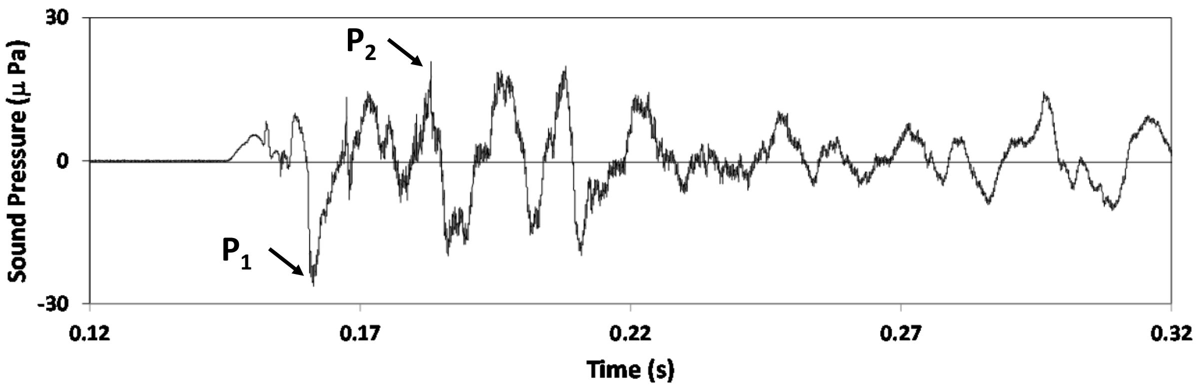



***Figure 18***. *Peak sound pressure computed from the maximum absolute value of instantaneous sound pressure that occurred over a 0.2 second time window.*

The maximum ($P_1$) and minimum ($P_2$) pressures, shown in Figure 17 for the start of the blast pulse given in Figure 18, are 26.3 psi (181.3 kPa) and 19.8 psi (136.5 kPa), respectively. The pressure difference is 46.1 psi and $SPL_{pk\text{-}pk}$ becomes 230 dB one micro-Pascal.

*Root-mean-square sound pressure level ($SPL_{rms}$)*

Because pressure fluctuates in water, it is often convenient to average this fluctuation in terms of a variance. As such, the SPL is calculated from the root mean square (RMS), or square root of the mean pressure of the waveform, to obtain a measure of time varying sound. This is a measure of cumulative sound pressure in terms of energy (pressure multiplied by time) over a selected time interval. The unit is generally used to describe the mean (or average) variance for continuous waveforms (often loosely referred to as the "mean power") and is given by the following formula:

$$SPL_{rms} = 10\ log_{10}\frac{1}{T}\int_{T1}^{T2} P\,(t)^2 dt = 20\ log_{10}\left(\sqrt{\frac{1}{T}\int P(t)^2\,dt}\right)\text{ dB re 1 µPa} \qquad (9)$$

where T is most often the duration of the signal. SPL becomes an "equivalent" continuous noise level that is a steady sound pressure level which, over a given time period, has the same total energy as the time varying pulse. RMS is often used for continuous signals and may have limited application to blast transients.

The RMS computed for the time integral of 0.2 s shown in Figure 19 is 6.6 psi or 45.5 kPa. $SPL_{rms}$ is 213 dB re one micro-Pascal which is similar to the $SPL_{pk\text{-}pk}$.

The duration selected for integration strongly influences the RMS value, though its definition is sometimes quite ambiguous. Where an SPL is used to characterize transient pressure waves, such as for underwater blasting or piling driving, it is critical that the time period over which the RMS level is calculated be specified. For instance, for a fairly uniform waveform of near constant frequency, the RMS of a 1.0 s window will be ten times higher than for a 0.1 s window. Hence, the longer the window, the lower the RMS and thus SPL.

For marine mammals, the RMS pressure historically has been calculated over the time interval of the pulse containing 90% of the acoustical energy (e.g. 90% $SPL_{rms}$) resulting in what is referred to as the "effective" sound energy of the impulse. The initial 5% and final 5% are excluded from the time window as shown in Figure 20. Equation (7) becomes:

$$SPL_{rms} = 20\ log_{10}\left(\frac{\sqrt{\int_{T_5}^{T_{95}} P(t)^2 dt}}{T_{95}-T_5}\right)\text{ dB re 1 µPa} \qquad (10)$$

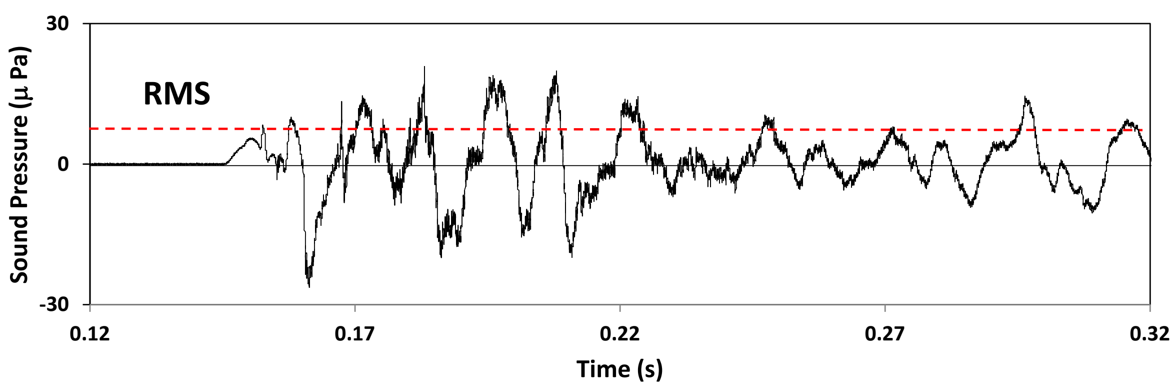



***Figure 19**. Root mean square (RMS) "equivalent" pressure for the 0.2 s window shown in Figure 18.*

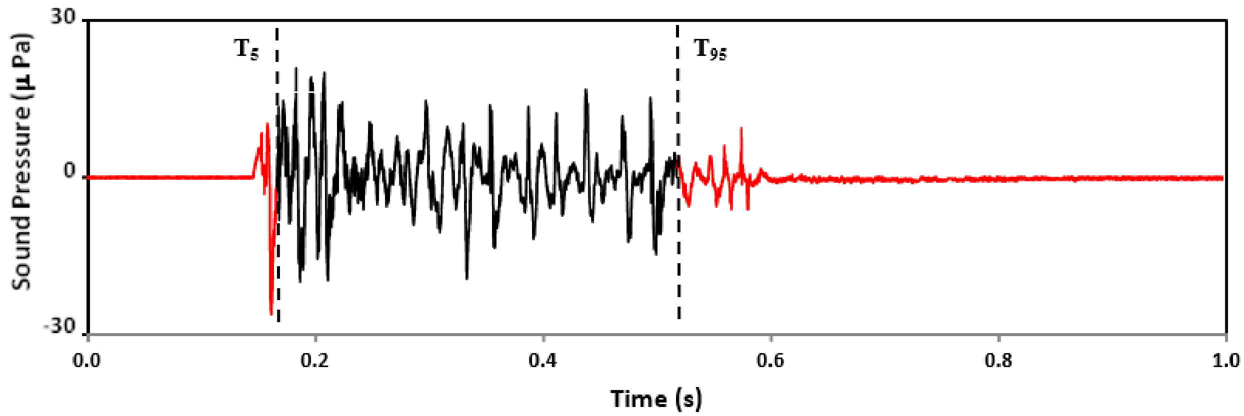



***Figure 20***. *"Effective" sound pressure level is computed for the time history containing 90% of the total energy (between $T_5$ and $T_{95}$) as given by the black wave trace (the red traces at the beginning and end are eliminated in the integration).*

The use of sound pressure level based on RMS should not be used for blasting as this metric is appropriately applied to continuous noise sources. Blasting produces a transient signal. Sound pressure level based on RMS computed over a set time window, longer than the duration of a typical blast, should not be applied to blasting.

*Energy Flux Density (EFD$_{dB}$)*

Often energy flux density is given in term of decibels and represents the sound exposure level of an impulse propagating as a plane wave in an unbounded medium given in term of decibels referenced to one micro-Pascal, per the following:

$$EFD_{dB} = 10\, log_{10}\left(\frac{EFD \cdot \rho \cdot c}{10^{-12}}\right) \text{ dB re 1 µPa} \qquad (11)$$

The term ρc is the acoustic impedance of water. The use of energy flux density in terms of decibels assumes that particle velocity in the water and the pressure pulse have the same phase and that frequency is a constant.

In reality, the acoustic signals from blasting form complex frequencies and the processing of measurements to obtain the total EFD$_{dB}$ becomes complicated. As previously pointed, out, the use of EFD based on pressure has been limited to date and impulse is a more common pressure measurement for fish injury correlations. Further, in shallow water and near-shore environments, as well as in near-field environments, pressure and velocity are complex quantities that most likely are not in phase.

*Sound Exposure Level (SEL)*

SEL is the time integral of the instantaneous squared sound pressure normalized to a squared reference pressure over a one-second period.

$$SEL = 10\ log_{10} \int_0^{Tmax} P\ (t)^2 dt \quad \text{dB re 1 μPa}^2 \cdot \text{s} \qquad (12)$$

where $T_{max}$ is the duration of the signal. The SEL measure represents the cumulative or total (not average as in the case of SPL) sound exposure or energy during a particular noise event with reference to a one-second time frame rather than the sound pressure. It is numerically equal to the $SPL_{rms}$ where T = 1 and the 1/T = 1. In effect it is SPL without the 1/T term and normalized to one micro-Pascal squared times seconds.

Unless otherwise stated, SEL is generally the sound exposure from a single event.

Equation (12) is often rewritten as

$$SEL = SPL_{rms} + 10\ log_{10}(T) \text{ dB re 1 μPa}^2 \cdot \text{s} \qquad (13)$$

and T is the duration in seconds.

The use of SEL for pile driving has been adopted by the California Department of Transportation in the Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish (Caltrans 2009). The time interval over which energy is computed for pile driving may not be appropriate for blasting.

*Cumulative Sound Pressure Level ($SEL_{cum}$)*

For multiple-pulse sources such as piles and rock hammers, multiple exposures may be summed to produce a single exposure "equivalent" value if the inter-pulse interval is too short for recovery from noise-induced hearing impairment (Southall et al. 2007). In that instance, the cumulative SEL (CSEL) is given as:

$$CSEL = 10\ log_{10} \left( \frac{\sum_{n=1}^{N} \int_0^T P_n(t)^2 dt}{P_{ref}^2} \right) \quad \text{dB re 1 μPa}^2 \cdot \text{s} \qquad (14)$$

which then becomes the form given by Strach et al. (2006):

$$SEL_{cum}(dB) = CSEL(dB) + 10log(N) \qquad (15)$$

and N is the number of strikes or pulse exposures. Note that Equations (14) through (15) were developed for non-blasting construction activities.

### 2.2.4 Frequency content

The shifting of frequency content of the seismic waves is always of interest as a potential mitigation measure. For ground vibrations, the goal is to increase frequency content in the ground such that potentially damaging ground displacements are lowered.

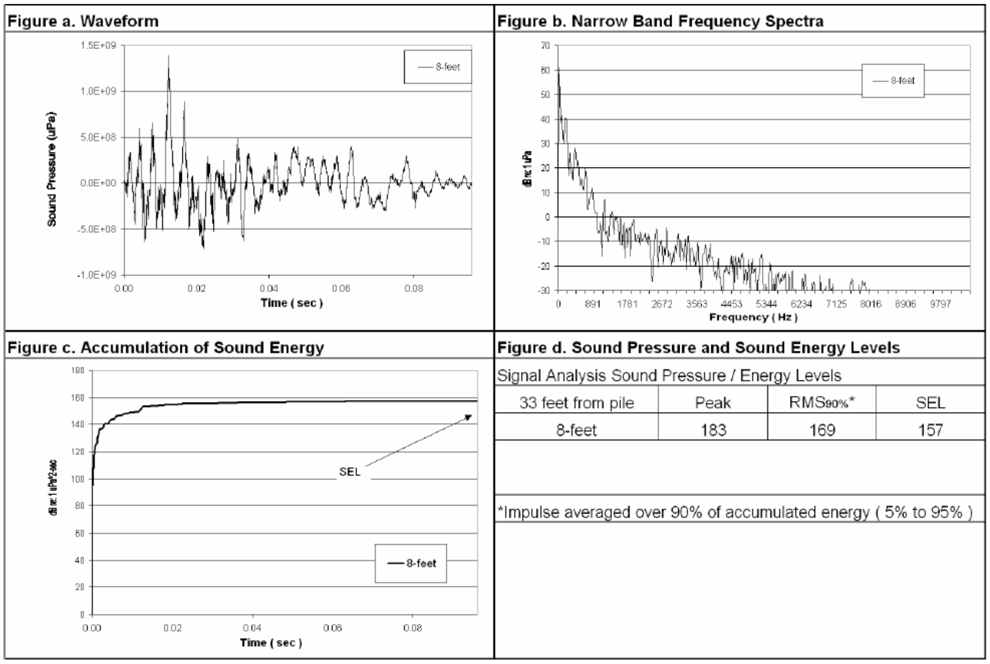
The opposite is true for water overpressure. The impulse or energy deposited into the water can rise quickly when high frequencies are present in the pressure time histories. *High frequencies impart high accelerations in the water that can have adverse effects which may result in tissue injury particularly when the positive and negative peak oscillations (or phases) arrive very close together in time.*

Fish response to water particle motions are relative to characteristic pressure time histories. *The authors of this white paper are unaware of any study in which water particle displacements have been quantified and correlated with fish injury.* Although it is difficult to "slow down" the rate of energy deposited into the water at the rock/water interface during production blasting, there are potential areas of future study that may modify blast frequencies deposited into the water by changing delay timing between blast holes, redesigning explosives mixtures, and increasing charge confinement during the detonation process. To date, there have been no systematic scientific studies that have measured the influence of blast design parameters on overpressure.

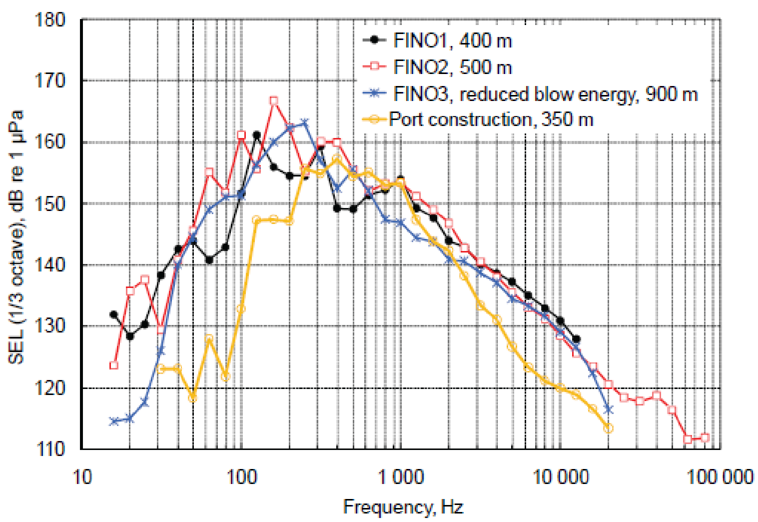
Frequency content of overpressure waves is handled somewhat differently than with ground vibrations. The measure of SEL takes into consideration the wide range of frequencies contained in impulse signals where peak pressures contained within the time histories can be associated with frequencies that may range more than four orders of magnitude ($10^0$ to $10^4$ Hz) which is greater than for blasting. The spectrum of frequencies are related to the RMS pressures measured and analyzed over a defined frequency bandwidth, as narrow as 1 Hz or, more appropriately, as an accumulation 1/3 octave (where an octave is a double of frequency).

The use of frequency spectra based on FFT and SEL frequency plots based on octaves are important for fish species in terms of determining physical injury and hearing loss, and for sound propagation and attenuation for prediction purposes. Plots of RMS pressure versus frequency as shown in Figure 21(a) are particularly useful when mitigation measures are being considered.

Underwater pressure pulses fluctuate in amplitude and frequency content and the relationships between sound energy level and frequency are required for meaningful analysis to understand the range or ranges of frequency at which most of the energy lie (data plotted this way are called ***sound spectrum***). An example of this kind of plot is given in Figure 21 (b). In this analysis, sound energy is analyzed in frequency bands referred to as octave or one-third octave bands in which sound pressure is analyzed over a specific range of frequencies and excludes all others. The word octave is borrowed from musical nomenclature and refers to a span of 8 notes. An octave has a center frequency that is $(2)^{1/2}$ times the lower cutoff frequency and has an upper cutoff frequency that is twice the lower cutoff frequency. The term bandwidth is used to describe the range between the upper and lower cutoff frequencies and the center frequency is that generally of interest for plotting the sound spectrum. The frequencies of interest in hearing range from 20 Hz to 20 kHz.




(a)




(b)

***Figure 21**. Examples of typical frequency content analysis for underwater sound in terms of sound pressure (upper right hand plot) (a) and in term of sound exposure using 1/3 octave bandwidths (b).*

Interestingly, the auditory sensitivity of humans, like that of bald eagles and other sensitive wildlife, begins at 20 Hz while for certain whales, it has been estimated to be as low as 7 Hz. The upper end for marine mammals such as whales and seals and sea lions is 16 to 20 kHz while for certain harbor porpoise species, the maximum sensitivity range can be 16 to 140 kHz. Hastings and Popper (2005) report that the functional hearing frequency range of fish is 20 to 1000 Hz and can vary within that range for each species.

### 2.2.5 Attenuation of blast overpressures

The most useful concept to consider when making underwater pressure measurements is the attenuation of pressures and frequencies both within the water column and as a distance from a transient energy source. The source energy (e.g., release rates and single and closely-spaced repeated events), propagation characteristic of the transmission medium, presence of underwater structures and geometry of boundary layers play important roles in the ability to predict and control injury and mortality to fish.

For blasting, the intensity of seismic waves in the ground and water overpressure decreases or decays with distance from the source according to scaling laws that measure distance with the geometry of the near-field wave front shape. The dimensionless scaling parameter that describes the attenuation of particle velocity and overpressure is the ratio of source-to-measurement distance divided by a measure of explosives charge weight raised to a power function that describes the shape of the initial wave front. This shape is defined for rock blasting on land by the cylindrical drill hole whose charge weight per linear foot of hole is defined by the cross-sectional area based on radius squared ($r^2$). Close-in the radiating wave front is cylindrical.

For underwater blasting where charges are detonated in the substrate, the pressure pulse into the water for the entire product blast surface is considered as a hemisphere, where the pressure intensity at the arc-shaped wave front is proportional to the radius cubed ($r^3$). Since the source energy of explosives based on the detonation charge mass is proportional to the wave-shape radius (a measurement of length) based on explosive density (mass per unit volume), the dimensionless scaling factor becomes $D/(W^{1/3})$ for overpressure, and $D/(W^{1/2})$ for ground velocity. *Scaling distance (D) with charge weight (W) allows two of the most important parameters that affect the intensity of water and ground energy to be properly evaluated for the purposes of prediction and control.*

The total amount of energy deposited into the ground or water per unit time period also dictates the intensity of PPV or sound pressure level (SPL). Extensive research by the U.S. Bureau of Mines (Siskind 2000) and others concluded that blast effects correlate best with the total mass of explosive charge (W) detonating within an 8-millisecond (ms) time window. Hence the attenuation of ground vibrations and water overpressure are dependent on the following scaled parameters:

Square root scaled distance, SRSD (or simply SD) $$\frac{D}{W^{1/2}} \quad (16)$$

Cube-root scaled distance, CRSD $$\frac{D}{W^{1/3}} \quad (17)$$

where D is the distance between the measurement location and closest blast hole generating the highest charge weight, W, over 8 ms.

The attenuation rate of peak pressure or particle velocity (PPV) as a function of scaled distance is chiefly dependent on the material properties of the transmission medium. Attenuation is determined using linear regression analysis on log-log axes in which measurements are plotted on the y-axis and scaled distance plotted on the x-axis as shown in Figure 22. The decay of peak pressures and velocities is exponential with distance from detonations. As such, plotting non-linear data on log axes will transform the exponential trend to a linear trend. A power curve fit is used to describe the linear best-fit with the following forms:

$$PPV = a * SRSD^{-b} \tag{18}$$

$$SPL_{peak} = a * CRSD^{-b} \tag{19}$$

Attenuation plots also can serve as a guide for blasters in the design of blasts to determine the appropriate charge weights and delay timing between blast holes to minimize the off-site effects of vibrations and water overpressure. The design of mitigation techniques can further be guided by a baseline site-specific attenuation model to move the best-fit line downward on the plot to minimize blast effects on fish.

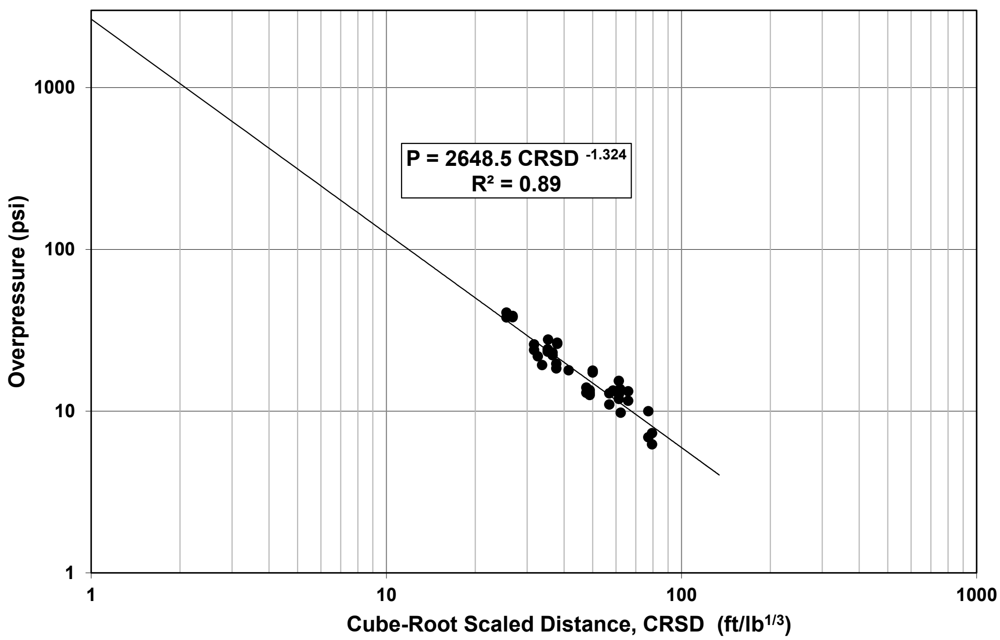



***Figure 22****. Example of water overpressure scaled distance attenuation using hydrophones placed at varying distances away from underwater production blasts using varying quantities of explosive charge weights per delay.*

### 2.2.6 Concluding comments on water overpressure metrics applied to blasting

The following are a number of observations regarding the use of various metrics to describe blasting impacts on fish:

- $SPL_{pk\text{-}pk}$ is used to describe short, high intensity sounds similar to those generated during underwater blasting where the use of $SPL_{rms}$ could underestimate the risk of acoustic trauma to fish without defining the correct time interval to assess impact.
- Bioacoustic impact assessment of marine mammals uses the $SPL_{rms}$ metric to establish safety "exclusion" zones around noise sources to avoid injury and to establish disturbance radii.
- Many criteria limiting SPL to protect fish during underwater blasting, as well as SPL reported from measurements during research studies, do not specify the computation

method used (peak-to peak or zero-to-peak, or RMS) nor do they specify the time interval over which integration impulse was calculated.

- Due to the historical absence of widely accepted definitions, method of measuring, processing and reporting SPL for impulsive sound, the application of reported SPL and impulse levels are not clear. Comparisons between distinct measurements are often difficult or impossible because it not clear which characteristic is being reported.

Based on these observations regarding metrics used to describe underwater blast effects on fish the following conclusions are made:

- There is no consistent method by which blasting impulse is measured and converted to sound pressure which leads to confusion when evaluating published measurements and criteria used by agencies.
- Sound pressure can be described in many different ways (average, peak, cumulative, and impulse levels). It is unclear which metric best correlates with fish injury from blasting.
- Sound pressure measurements from continuous, repetitive noise sources have been used to describe impacts to fish in the past. The application of the results from these studies to one-time transient noise sources such as blasting is unclear.
- Log-transformation of pressure measurements is not an intuitive process to most construction project managers, biologists, blasters, engineers and compliance personnel on rock removal projects. An advanced understanding of acoustics is needed to understand permit requirements and compliance reporting when underwater blasting is required.
- There is no standard measurement distance from a noise source or position within the water column to measure potential blasting impacts to fish; limits set to protect fish commonly state that measurements take place "where fish are present".
- Several studies have attempted to correlate explosive source energy with distances and fish injury; however, there are far too many uncontrollable variables that prevent useful correlations.
- There is little or no data available on the attenuation or decay of blast-induced noise levels with distance from the source in or near water to rely upon for prediction and mitigation.
- Physiological and behavioral effects on fish are difficult to quantify as specimens are not easily observed in their natural habitats.
- Guidance criteria and project specifications are needed for blasting operations occurring in and near water bodies as they pertain to fish injuries.

# CHAPTER 3 – AVAILABLE MONITORING EQUIPMENT AND MEASUREMENT STANDARDS

## 3.1 VIBRATION AND AIRBLAST EQUIPMENT AND MEASUREMENT STANDARDS

Blasting-type seismographs used to measure and record ground vibrations and air overpressures meeting performance specifications published by the International Society of Explosives Engineers, ISEE (2011) are available from a number of companies. The type and model of various seismographs may be obtained through the ISEE (www.isee.org).

General guidelines for field deployment were previously discussed. Although seismographs are manufactured with air overpressure microphones to capture airblast when blasting on dry land, airblast microphones are not generally used for underwater blasting when tri-axial geophones are required to monitor river substrate. Airblast microphones are often required when blasting near wildlife habitat in the dry.

Blasting seismographs are sold with software used to download, analyze and report blasting events. The software is proprietary and can only be used with the seismograph brand purchased. Each manufacturer offers different software features and it is recommended to become acquainted with the software before selecting a seismograph brand to purchase.

### 3.1.1 Geophones

Geophones should be tri-axial transducers such that three components of ground vibration are recorded to determine the maximum peak particle velocity (PPV) in any one component.

### 3.1.2 Geophone sampling positions

Geophone placement for the development of a site attenuation model requires that sensors be positioned in a linear array in doubling distances beginning as close-in to the blast as safely possible. Most seismographs can record ground vibration up to 10 in/s. Care is taken not to saturate the maximum amplitude at the closest location. It is recommended that 5 to 6 geophones be included in the array. A total of 30 measurements are considered statistically sufficient to apply linear regression analysis and achieve a correlation coefficient of at least 85% for the best-fit line.

### 3.1.3 Geophone sampling rates

Sample rates of 1,024 samples per second (S/s) for low predominant frequencies below 20 Hz and 2,048 S/s for high frequencies above 20 Hz are appropriate. In some cases higher sample rates may be justified. A total sample interval for blasting is at least 5 times greater than the total time of the blast determined by summing all the individual delay times for all blast holes.

### 3.1.4 Seismograph calibration

Annual calibration of the transducers is recommended by all manufacturers. This requires the unit be sent to a certified calibration engineer or back to the manufacturer for shaker table frequency-amplitude adjustments if needed. In addition, it is a good idea to upgrade firmware and check the status of the internal battery for replacement if necessary.

## 3.2 WATER OVERPRESSURE EQUIPMENT AND MEASUREMENT STANDARDS

### 3.2.1 Hydrophones

*There are no available uniform standards for the manufacture and measurement of water overpressures resulting from impulsive energy sources*. Passive transducers are used to measure pressure fluctuations created by external energy sources as opposed to the active type transducers used in sonar. Hydrophones are a type of electroacoustic transducer and are referred to as pressure sensors and less often as microphones. Two types of hydrophones commonly used to measure blast pressures are piezoelectric crystals and piezoelectric ceramics. Piezoelectric transducers consist of a crystal element (usually quartz or tourmaline) encased in a silicon fluid or polycrystalline materials that come in various shapes and sizes. Transducer performance is specified by working ranges of pressure, frequency response and sensitivity and used with high speed data acquisition systems to measure and record underwater overpressures. The output from the pressure sensor is a pressure-time history similar to that of a velocity transducer with a peak amplitude, pulse duration, and frequency at the peak.

*Regardless of the metric used to determine blast strength, monitoring methods can have a great influence on the accuracy of underwater overpressure measurements*. Such factors to consider include hydrophone placement in the water column, distance from the source and sampling rate. Other factors that can affect the measurement results include the measurement data quality including the presence of water currents at the sensor, water temperature, reflecting boundaries at the water/air interface as well as at the bottom of the water body (e.g. soft mud versus hard rock).

### 3.2.2 Hydrophone sampling positions

Spatial distribution of hydrophone placement is usually guided by the anticipated location in the water column of a particular fish species thought to be present in the water at the time of blasting. No protocols exist for hydrophone position in the water column when conducting hydroacoustic measurements of blasting. For blast measurements, depth in the water column and distance from the point at which the rock pressure pulse enters the water body is critical for repeatable measurements and to capture boundary reflections at the water-air interface.

Recent attempts during pile driving have been made to use a standard distance of 1 m away to report cumulative energy or peak pressures which provided a good basis of comparison when considering mitigating noise sources. The term is referred to as source level measurements defined as the sound (SPL) at a nominal reference distance of 1 m, expressed in dB re 1μPa·m.

Recommendations for hydrophone placement during pile driving were provided by the National Marine Fisheries Service (California Department of Transportation, Caltrans, 2009). One sampling position 33 ft (10 m) from the pile at midwater depth was recommended as a standard reference distance for small piles. In 2013, the Fish Habitat Working Group (FHWG) developed a monitoring report template to provide additional guidance for monitoring attenuation with distance using multiple hydrophones. It was suggested to place all hydrophones at least 3.3 ft (1 m) below the water surface. If only one hydrophone is used it should be placed 10 m from the pile at midwater depth.

*Regardless of the source, the overwhelming data on SPL measurements and computed SELs are presented without reference to measurement locations relative to the sources rendering the data useless*. Standardized measurement distances and depths may be difficult to establish based on the variable manner in which the source energy propagates into the water.

### 3.2.3 Hydrophone sampling rates

Based on the extremely high frequencies that blast pressure time histories can generate in water, it is the authors' experience that pressure-time sampling rates must be well in excess of 0.250 to 1 M S/s. High samples rates are required to capture peak pressures for accurate analysis. All too often the sample rate of data acquisition systems are not reported for research or compliance measurements.

Sampling rates for sound pressure measurements for acoustic measurement generally range from 2,500 to 250,000 S/s depending on bandwidth. Some monitoring systems use up to 1 M S/s for certain marine environments. For continuous monitoring of construction vibration the amount of data collected can be unnecessary and overwhelming for storage and processing.

### 3.2.4 Hydrophone calibration

Instrumentation calibration of hydrophones should be verified in the field prior to conducting measurements with a calibrator supplied by the manufacturer or by the manufacturer at a calibration facility. Ideally, field calibration is done in a quiet environment where the equipment is to be deployed, just prior to conducting measurements. Side-by-side measurements between sensors can be used to verify pressure time history agreement as a calibration check to determine if costly factory calibration is necessary.

(blank page)

# CHAPTER 4 - ADVERSE EFFECTS ON FISH FROM BLASTING AND CONSTRUCTION ACTIVITIES VIBRATION

## 4.1 FACTORS INFLUENCING FISH RESPONSE TO OVERPRESSURES

Construction activities occurring in or adjacent to water bodies have potential to impact aquatic species by altering conditions in ambient pressure and particle motion in water. While other aquatic species may be impacted, fish and fish habitat are an important resource and construction projects that may impact them often require federal, state, and local permits. This section explains how sudden changes in pressure can affect fish and summarizes a selection of empirical study results that have examined the hydroacoustic effects of blasting and pile driving on fish.

There are more than an estimated 32,500 living species of fish in the world and nearly 1,000 species of freshwater fish in the United States (Froese and Pauly 2013). Research on the impacts of blasting has only been completed for a small number of species. There are many aspects to consider when assessing the effects due to variation in life history and physiological characteristics of the many species. For instance, some species may be more susceptible to the effects of pressure changes if they have swimbladders or are hearing specialists. Body shape and construction should also be considered as a rigid body wall construction could decrease flexibility and increase injury. Fish with laterally compressed bodies may have more surface area to receive shock waves than cylindrically-shaped fish. Smaller fish may also be more vulnerable than larger fish (Yelverton et al. 1975) making juvenile and early life stages more susceptible. Sexual maturation and reproductive strategies are important life history aspects to consider. It is important to note that life histories of some fish seasonally place them in different habitats and, clearly, if a fish is not present it will not be affected by changes in ambient conditions. For example, many pacific salmon species are spawned and hatch in freshwater streams where they will spend a portion of their early lives. Some species will leave the stream almost immediately for estuarine and intertidal areas to feed and grow before spending a period of years in the ocean, while others will rear in their natal streams for more than a year. After spending time in the ocean, adult salmon will return to the same stream they were born in to reproduce and die. Depending on the salmon species' life history, short-term vibration producing projects in or near known salmon streams may sometimes be scheduled to avoid direct impacts to fish.

Other factors such as the physical orientation of the fish to the blast, distance from the blast, position in the water column, duration of exposure, time between exposures, and habitat type may all play a role in the degree of injury a fish sustains from exposure to blast overpressures. Indirect or secondary effects such as increases in sediment, turbidity, toxicity, or other physical alterations to habitat could reduce fitness or survival by selectively removing food sources or by making them more vulnerable to predation.

## 4.2 OVERPRESSURE EFFECTS ON FISH WITH EMPHASIS ON BLASTING

Barotrauma injuries are the physical damage resulting from quick changes from ambient pressure and are assessed through gross anatomical and microscopic exam of tissue. The effects of sudden changes in overpressure can range from physical injury, behavioral response, temporary or permanent hearing loss, to mortality in extreme cases.

Physical barotrauma injuries include injuries to the swimbladder, hemorrhaging, embolism, liver and other visceral organ damage, changes in stress hormones, damage to the octavolateral system, and scale loss. Swimbladder injuries have been well documented and are the most commonly damaged organ in fish that possess them (Yelverton et al. 1975, Goertner et al. 1994, Govoni et al. 2003, Godard et al. 2008, Carlson et al. 2011). Swimbladders expand and contract with external pressures and, in the event of rapidly changing pressures, negative pressures subject the swimbladder to tensile forces causing it to expand and damage surrounding organs and tissues and to burst in extreme cases (Simmonds and MacLennan 2005). Healing and recovery from swimbladder injuries has been observed under ideal conditions (Wiley et al. 1981, Casper et al. 2011) but may be more difficult in natural conditions as fish may become more vulnerable to predation without the ability to regulate buoyancy (Govoni et al. 2003). Species with thick-walled swimbladder have been observed to be more resistant to shock in some instances (Fitch and Young 1948; Gaspin et al. 1975).

Other types of barotrauma injuries include internal damage resulting from swimbladder oscillation including torn ribs, ruptured body walls, intestines, organs, peritoneum damage, stomach eversions, and vent prolapse (Kearns and Boyd 1965, Houghton and Munday 1987, Carlson et al. 2011). Lethal and non-lethal hemorrhaging has also been observed internally and externally (Godard et al. 2008) and embolisms resulting from accumulation of gases from extreme pressure differences have been observed in gills, fins, hearts, swimbladder, and kidneys. Embolisms can also result in the outward displacement of eyes (Godard et al. 2008, Carlson et al. 2011).

The octavolateral system in fish is responsible for mechanosensory functions including auditory, equilibrium, lateral line, and electrosensory systems when present. Hair cell sensor receptors in these systems can be damaged causing temporary or permanent hearing loss and disruption in orientation and locomotion, predator detection, and navigation (McCauley et al. 2003, Goertner et al. 1994). Fish that are hearing specialists (e.g. herring, shad) have connections between their swimbladders and inner ear increasing hearing range and sensitivity thus making them more susceptible to extreme pressure changes. Injury to the octavolateral system in fish could present as a behavioral response. Changes in stress hormone levels could also cause behavioral changes making some fish more susceptible to predation (Sverdrup et al. 1994).

### 4.2.1 Classification of injuries

*There is no agreed upon injury classification system to assess post-blast exposure condition of fish*. Hubbs and Rechnitzer (1952) used as classification system with five degrees of injury; others have used 7 and 3 degrees of injury (Teleki and Chamberlain 1978, Houghton and Munday 1987). Carlson et al. (2011) used a new approach termed the "Fish Response Severity Weighted Index" (FRSWI) that provides a weighted sum of the number of injury types and severity based on the physiological cost to the fish and how likely injuries are to affect performance and survival. This new approach has been applied to several studies examining the hydroacoustic effects of pile driving on fish facilitating the comparison of study results. *In many cases, the exact method or system of injury classification is not detailed in research and publications and the level of injury that is considered lethal is unclear*.

There have been many empirical and observational studies conducted to assess the effects of blasting on fish; however, variables in study design, level of detail reported, and overall conclusions complicate comparisons. For example, many observational studies have documented the number of fish kills observed without mention of crucial source energy variables such as maximum pounds per delay or distance from the blast. Other studies have utilized theoretical equations to determine water overpressures attenuations in lieu of actual pressure measurements. *In order to identify what levels and which parameter of blast strength cause injury and mortality in fish, comparison of studies must be limited to those performed under similar, controlled conditions*.

### 4.2.2 Comparisons of caged fish blasting studies on salmonids

Salmonids are a group of fish belonging or pertaining to the family Salmonidae, including the salmons, trouts, chars, and whitefishes. They are of particular interest for blasting impact study as many salmonid species have experienced declines in abundance during the past several decades as a result of human-induced and natural factors. Several blasting impact studies have been conducted on caged salmonids where pressures were measured and thus can be compared.

Figure 23 summarizes the results of various investigations that examined the effects of blast induced overpressures on caged salmonids. Peak measured pressures in the cages are given in the form of a histogram. The study comparison (Kolden and Aimone-Martin 2013) was completed for the Alaska Department of Fish and Game (ADFG) as supporting information for the Alaska Blasting Standard for the Proper Protection of Fish (Timothy 2013).

The results of the studies are varied. Three studies reported no effects or injury to caged fish exposed to 2.7 to 290 psi (19 to 1,999 kPa). Conversely, injury and mortality were recorded at exposure levels as low as 10.0 psi to 285 psi (69 to 1,965 kPa). These results demonstrate the lack of agreement among studies and illustrate the difficulties of determining exact amounts of instantaneous overpressure changes that fish can withstand. *While all studies compared involved caged salmonids exposed to measured blast induced pressure changes, the degree of explosive confinement and method of measuring overpressures differed and likely influenced results*.

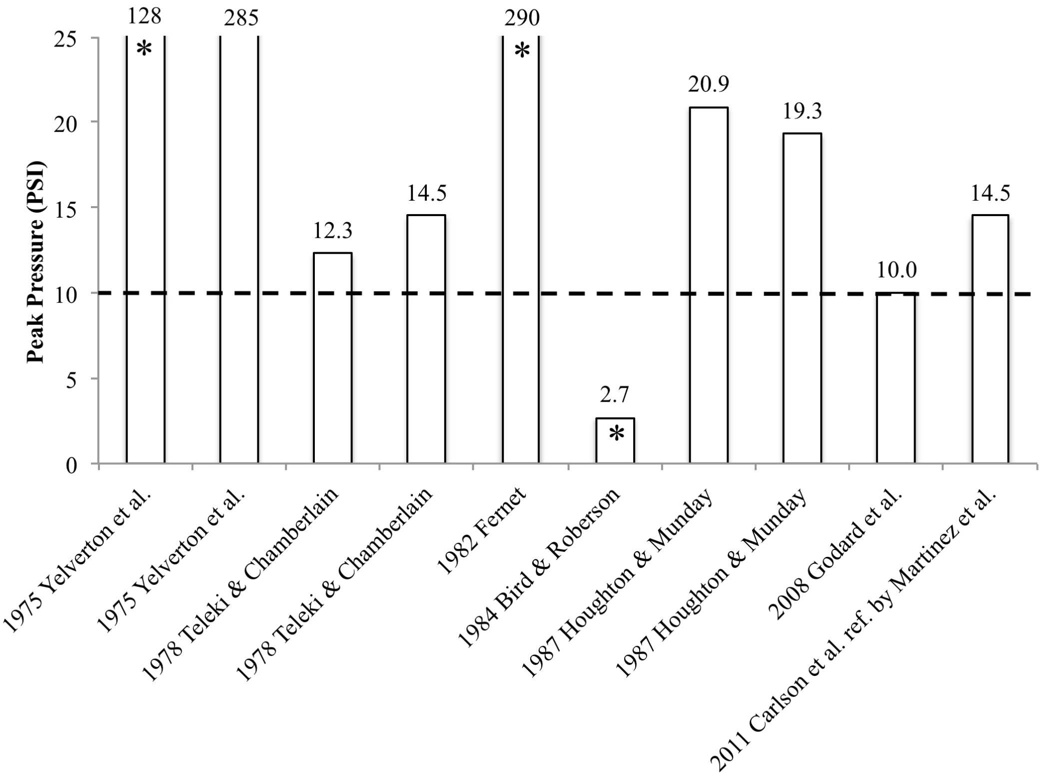



***Figure 23***. *Reported blast peak overpressures for caged salmonid studies. The dashed line (10.0 psi) indicates the lowest peak overpressure where salmonid injury was documented (Godard et al. 2008). Asterisk (*) represents reported peak overpressures where no injuries or mortalities were observed.*

## 4.3 MECHANICAL SHOCK – VIBRATION EFFECTS ON EMBRYOS

Ground vibrations that enter into a water body substrate may impose mechanical "shock" to a developing embryo. Transient impulse vibrations from blasting can induce physical deformations to the eggs themselves or have the potential to dislodge eggs from the substrate. Extreme displacement of surrounding gravels can tear or crush the stationary embryos.

*The amplitude of blast-induced vibrations at which embryos can be damaged or dislodged is not well-established*. The sensitivity of fish eggs to physical disturbance has been well documented in laboratory studies using qualitative means of generating peak particle velocities (PPVs). However, this work has primarily focused on determining sensitive stages to disturbances, instead of determining critical exposure levels.

Embryo tolerance to physical shock has been examined as early as the 1950's to improve success at hatcheries responsible for incubating and hatching young salmon (Smirnov 1955). Embryo sensitivity to shock varies throughout development and salmonid embryos studied were the most susceptible to shock damage during the developmental phase epiboly and more tolerant in later stages of development (Smirnov 1955, Jensen and Alderdice 1983 and 1989, Faulkner et al. 2008). *Many of these shock experiments were conducted in the laboratory using methods thought to simulate blasting but by no means simulated the physical model of eggs within a gravel bed with flowing water*.

The Canadian Department of Fisheries and Oceans (DFO) developed guidelines for blasting that contain maximum allowable limits for both overpressure 14.5 psi (100 kPa) and PPV 0.51 in/s (13 mm/s) in a spawning bed during egg incubation (Wright and Hopky 1998). Blasting guidelines imposed by the Alaska Department of Game and Fish (ADFG 1991) limited instantaneous pressure changes to 2.7 psi (19 kPa) and PPVs to 0.5 in/s (13 mm/s) and have since been raised to 7.3 psi (50 kPa) and 2.0 in/s (51 mm/s) for overpressures near fish and PPVs near incubating embryos respectively (Timothy 2013).

The scientific merits of these limits are not clear. More recent studies (Faulkner et al. 2006) have shown that PPV measurements of 1.12 in/s (28.5 mm/s) did not increase egg mortality in gravel bed control sites during a blasting study at a mine site. However the embryos were beyond the critical stage of development most sensitive to vibrations. In a different study, Rainbow trout (*Oncorhynchus mykiss*) embryos were held in plastic bags filled with water and exposed to seismic charges detonated in the frozen substrate of a lake. Overpressures were recorded up to 40.6 psi (280 kPa) and there were no significant differences in mortality between exposure and control groups (Godard et al. 2008). To date, these are the only two studies that have related the mechanical effects directly from blasting to embryo mortality.

Figure 24 shows the results of laboratory studies that examined the resistance to shock for several salmonid embryos reviewed for ADFG in Kolden and Aimone Martin (2013). The results of the mine study mentioned above (Faulkner et al. 2006) are also shown. The lowest PPV level for which embryo mortality was reported in lab tests was 5.8 in/s (147 mm/s) and is well above the recommended DFO maximum limit for protection of embryos in spawning beds of 0.5 in/s (13 mm/s) in Canada (Jensen and Alderdice 1989, Faulkner et al. 2006, Faulkner et al. 2008).

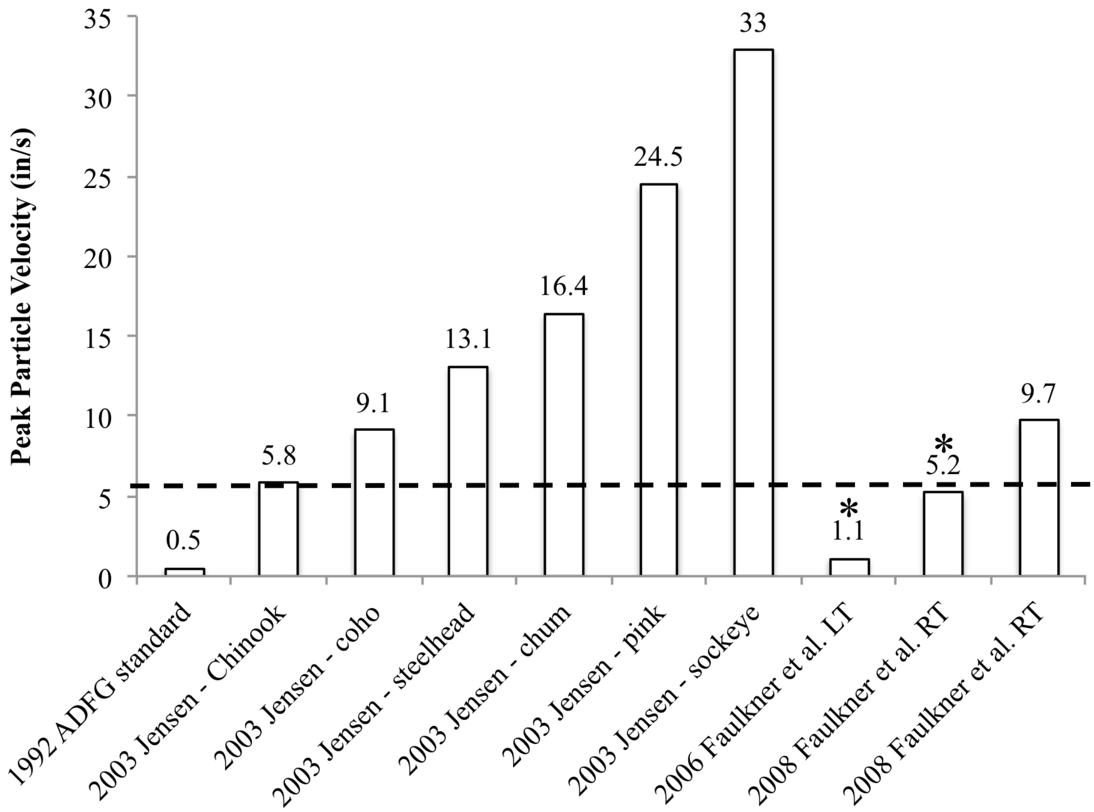



***Figure 24***. *Reported PPVs salmonid embryos were exposed to in mechanical shock tests. Dashed line (5.8 in/s) indicates the lowest measured PPV that caused mortality (Jensen 2003). Values with asterisk (*) indicate reported exposures that did not cause mortality. LT = lake trout, RT = rainbow trout.*

# CHAPTER 5 - DISCUSSION OF METRICS TO DESCRIBE BLAST OVERPRESSURES

It is clear that well-controlled studies correlating fish injury and mortality to a single metric are lacking. The accumulation of energy over time or impulse has been reported as a measure of blast strength and correlated with injury based on fish size (Yelverton et al. 1975). Others have reported peak pressure as the strongest correlating parameter (Houghton and Munday 1987, Carlson et al. 2011).

Richmond et al. (1973) and Govoni et al. (2003, 2007) found that impulse was best correlated with injury and mortality. Gaspin et al. (1975) reported that impulse predicted mortality better only at depths less than 9.8 ft (3 m) and others have stated that impulse was not a good predictor of fish damage for confined charges (Munday et al. 1986).

Unfortunately, methods for calculating impulse have varied from selecting time intervals containing only a single peak, including only positive or negative values, or as an average over the entire time history, as discussed previously in this paper. Cole (1948) identified the problem of establishing an upper time limit ($T_2$) for integration as this upper limit can greatly influence the impulse reported. Explosions create short-lived transient pressures followed by a chemical reaction of explosion forming gas products. Including longer-term pressure responses at very low amplitudes in the calculation can greatly affect the final impulse. As such, the exact method of calculating impulse is important when comparing study results pertaining to injury and mortality of fish. Confined blasts have a longer positive pressure phase than unconfined open water blasts that have steep rise times which create elevated impulse values making comparisons difficult. Specifically, it is important to know the time interval used and which components of the shock wave were integrated (i.e. initial pulse, subsequent reflections, positive only, negative only, etc.). Other factors that have been found to influence the final impulse strength calculations include the frequency response of the measurement system (Munday et al. 1986).

Energy flux density (EFD) is not widely used to assess blast effect on fish. The use of $EFD_{dB}$ has been criticized in that it tends to emphasize measurement variability with the squared term that tends to amplify any measurement error. Current literature suggests that EFD only be used at great depths or at far-field distances since it does not account for surface pressure release (Simmonds and MacLennan 2005).

*Distance effects on fish injury are absent in an overwhelming majority of studies*. Hastings and Popper (2005) clearly state the degree of damage to fish is not related to distance from pile driving but to the received level and duration of the sound exposure. Monitoring data show that sound pressure levels (SPL) do not necessarily decrease monotonically with increasing distance from the pile. Unfortunately, many studies that intended to correlate exposure metrics (e.g. SEL) with mortality and damage levels for situations without and with mitigation (e.g. bubble curtains) failed to show any correlations due to a small sample size (Caltrans 2009).

As mentioned earlier, underwater overpressure blast strength can be calculated in several ways including peak amplitude and impulse strength. Further research is necessary to determine which parameter best correlates with fish injury and if the same parameter can be used in attenuation models to best predict blast strength at distances from the source. In the case of both blast induced water overpressures and ground vibrations it is important to record and report how the data were recorded (e.g. sample rate, sensor position, source energy) and clearly identify the method used to calculate final values. Time duration and limits of the signal selected for calculation are crucial to determine the correct time weighted impact measure.

***The body of scientific and commercial data currently available appears to be inadequate for the purpose of developing more than the most preliminary scientifically supported criteria that will protect fish from exposure to pile driving sound and blast induced overpressures.***

# CHAPTER 6 - MITIGATION MEASURES

Several mitigation measures to control and limit vibrations and overpressures are often incorporated into project design. Mitigating measures cannot always offset 100-percent of blasting impacts and can be costly and difficult to implement. In some cases, mitigation measures can be dangerous to implement and may cause more damage to fish or fish habitat than blasting alone. The effectiveness of the measures can depend on many variables including species present, site terrain and flow conditions, weather, and many more. Keevin and Hempen (1997) provide an overview of mitigation techniques. Common mitigation measures that can be incorporated into projects are summarized below.

## 6.1 WORK WINDOW TIMING RESTRICTIONS

The simplest and most effective method to avoid impacts from blasting is to work during times when fish species are not present in the water. If species are always present, work can occur during a time when they are the least sensitive to impacts if possible. Difficulties may arise if project scheduling or design require blasting occur during specific conditions (e.g. low-flows, seasonal, tidal, etc.). Local permitting and natural resource agencies have specific knowledge on species and habitats in the area they are responsible for.

## 6.2 FISH REMOVAL

If fish presence cannot be avoided, physically removing fish from an area can minimize impacts. Some methods of fish removal include trapping, netting, electrofishing, or dewatering an area. Fish removal is effective on many projects but can be costly or dangerous when site conditions are not ideal (variable or high flows, deep water, dangerous terrain). Fish removal often requires training and permits as incorrect handling can cause undue stress and injury. It can be difficult to locate and remove 100-percent of small and juvenile fish from large or complex areas.

## 6.3 DIVERSIONS OF RIVERS AND STREAMS

Temporarily diverting rivers and stream during construction may be possible during times of low baseflow volumes. When combined with fish removal into temporary holding ponds or tanks, diversions have been used successfully in large river system such as the Rio Grande and South Platte Rivers. Methods include constructing berm or coffer dams and piping or pumping water. In some cases diversion may cause more sediment disturbance. Other factors to consider are possible diversion failure, public safety, legal, environmental, regulatory and economic consequences.

## 6.4 SCARE CHARGES

Methods of fish deterrents designed to scare fish from an area include detonating scare charges, hazing fish with watercraft and personnel, and audio technologies. The use of scare charges using small blasting caps can be effective and should be deployed 30 to 60 seconds prior to the main production blast. Higher charge weight scare charges can be more harmful than effective (McAnuff et al. 1994, Keevin et al. 1997). Acoustic deterrents consist of a steady or pulsed tone played underwater. This method has been effective in some instances but different species may respond differently to various acoustic frequencies and amplitudes. In one instance, migrating Atlantic salmon smolt (*Salmo salar*) were successfully deterred in a small river with a 10 Hz tone

(Knudsen et al. 1992). Strobe lights have been tried and were found ineffective in high turbidity situations (Racca et al. 2004).

## 6.5 BUBBLE CURTAINS AND BARRIERS

Bubble curtains are designed to create a barrier of bubbles in the water column around an activity and cause pressures to attenuate as they cross the bubble barrier. Bubble curtain systems can be constructed in several ways including forcing compressed air through a single or multiple pliable hose system, rigid metal pipes, or manifolds (Hempen 1993).

Effectiveness of bubble curtain use varies and has been documented in a few instances. Keevin et al. (1997) showed that use of a bubble curtain in deep, swift, turbulent water significantly reduced mortality of caged bluegill (*Lepomis macrochirus*) during demolition of a dam and locks on the Mississippi River. However, high cost, time, and installation difficulty were noted as drawbacks (Keevin et al. 1997). Deployment of a hose based bubble curtain during blasting in a relatively protected area effectively reduced peak water pressures and the mortality radius for pacific herring (*Clupea pallasii*) and surf smelt (*Hypomesus pretiosus*) (Grogan 2005). Others have concluded that bubble curtains are ineffective in conditions with river of high flow rates (Fernet 1982; McAnuff 1994) and extremely expensive to install and operate (McAnuff and Booren 1989).

Additional types of pressure inhibiting barriers include air and steel sheeting. Air-entrained sheeting consists of closed-cell foam or bubble wrap and has been suggested as a highly effective means of reducing pressure in still water environments (Hempen 1993). Steel sheeting barriers, or sheet piles, have been required on several projects to reduce pressures and sedimentation but the effectiveness of these methods is unknown.

In summary, bubble curtains have been shown to be effective for pile driving and less so for in-water blasting.

## 6.6 VISUAL MONITORING WITH A PRE-DEFINED SAFETY ZONE

Observer “watch circles” for visual monitoring and acoustic surveys performed by trained personnel can help identify when a species of interest is in the area. Some blasting programs are designed to have watch circles for marine mammals, turtles, or birds in the area so that blasting can be postponed or delayed until they leave the area. In cases where it is difficult to observe the species of interest (e.g. the species rarely surfaces, is a small fish, turbid water, etc.) acoustic water surveys and sampling techniques can assist. Surveys and sampling methods can be effectively used before and after blasting to estimate the number of fish in an area or the amount of fish take during a blast. Watch programs should commence approximately one hour prior to blasting and end one-half hour after the blast.

## 6.7 MODIFICATIONS TO PILE DRIVING METHODS

The use of cushion blocks placed on the top of pile to lessen the blow energy, sheet piles to serve as cofferdams and large casings around piles have been effective in reducing sound pressure levels. Blocks made of wood, nylon, and plastic composites such as Micarta™ have been used to attenuate sound levels. Other measures such as sheet piles or large casings emplaced around the pile can reduce sound pressure into the surrounding water. However, the method of installation may create excessive bottom disturbance, increase turbidity, and introduce contaminated sediments into the water

## 6.8 BLAST DESIGN MODIFICATIONS TO COMPLY WITH PERFORMANCE SPECIFICATIONS

Vibration and overpressure performance based specifications promote the use of best management practices to ensure safe blasting using state-of-the art products and techniques. A number of blast design modifications can be implemented to ensure compliance with specifications. Blast design modifications should be applied by blasting experts on a case-by-case basis. Some of these include the following:

- reduce the charge weight per delay;
- increase the amount of stemming at the hole collars;
- deck the charges in the blast hole;
- change the delay timing for all holes;
- re-orient the delay timing along the rows and the burdens directions, effectively changing the sequence of initiation; and
- reduce the surface area of the blast by shooting more, smaller blasts.

Specifications that prescribe blasting methods or techniques may be difficult or unsafe to implement and do not always ensure compliance with safe vibration and overpressure amplitudes.

(blank page)

# CHAPTER 7 - APPLICABLE CRITERIA

In the rock blasting industry, regulations or project limits are often specified in terms of zero-to-peak pressure and the peak is reported regardless of the phase in which it occurs. Impulse is often required to be reported but its correlation with fish damage is not well-defined. Criteria to limit fish injury based on impulse have not been established even though this metric may be of interest to some fish protection agencies.

## 7.1 GROUND VIBRATION AND OVERPRESSURE CRITERION FOR BLASTING

There are limited criteria set for blasting to prevent injury to fish or eggs in spawning beds. Suggested guidelines have been established in Canada (0.5 in/s, 13 mm/s) and Alaska (2.0 in/s, 51 mm/s) as previously discussed. Supporting documentation does not provide clear justification for the stated limit (Wright and Hopky 1998). The recently updated Alaskan guideline was selected as a limit that is "below levels that have been shown to cause injury or mortality to salmonids and salmonid embryos and provides a baseline for pressure and vibration monitoring that will aid ADF&G in assessing the effectiveness of the standard to properly protect fish and embryos" (Timothy 2013). This guideline level was raised from the previous guideline limit of 0.5 in/s established in 1991.

Established criteria defining the maximum allowable overpressure for the protection of fish are also limited to Canadian and Alaskan guidelines. The Pacific Region Department of Fisheries and Oceans (DFO) limits blast overpressures to 14.5 psi (100 kPa) based on the guideline document by Wright and Hopky (1998). Canada's Northwest Territory (NWT) applies a lower limit of 7.3 psi (50 kPa) based on an empirical study that exposed juvenile rainbow trout to seismic charges detonated under 3 to 10 ft (1 to 3 m) of clay substrate (Godard et al. 2008). Overpressures at the fish cages were measured and significant injuries including eye distension and hemorrhaging were observed in test specimens at 10.0 psi (69 kPa). Thus a cautionary limit was selected to protect fish. The Alaska Department of Fish and Game (ADFG) guidelines were recently raised from (2.7 psi, 19 kPa to 7.3 psi, 50 kPa) based on the above study and other studies reviewed for the ADFG (Kolden and Aimone-Martin 2013). The review examined empirical studies where caged juvenile salmonids exposed to blasts and overpressures were monitored. Based on the review, the authors concluded that the injury level reported by Godard et al. (2008) was the lowest known peak pressure to cause injury, thus the ADFG adopted the same limits as Canada's NWT.

## 7.2 PILE DRIVING CRITERIA: FISHERIES HYDROACOUSTIC WORKING GROUP

The Fisheries Hydroacoustic Working Group (FHWG) was established to address issues regarding impacts to fisheries from underwater sound pressure created by pile driving. The FHWG includes representatives from the Federal Highway Administration (FHWA), California Department of Transportation (Caltrans), Departments of Transportation in Oregon and Washington, NOAA Fisheries (Southwest), NOAA Fisheries (Northwest), U.S. Fish and Wildlife Service, California Department of Fish and Game, and the U.S. Army Corps of Engineers, and a panel of hydroacoustic and fishery experts. The group compiled information from scientific studies providing a basis for underwater sound effects on fish and recently developed an underwater noise monitoring plan template.

Caltrans developed a guidance manual for pile driving projects including mitigation and monitoring techniques for pile driving activities. The technical guidance document explains the fundamentals of hydroacoustics as they apply to pile driving, a chapter on the effects of pile driving on fish, and a chapter detailing the regulatory and permitting requirements for pile driving activities and information on how potential effects are evaluated. The Guidance Manual provides an in-depth overview of pile driving and its effects on fish relevant to regulators and project planners alike.

A hydroacoustic compendium of past projects is included as an appendix within the Caltrans Guidance Manual. The compendium contains empirical data on sound pressures recorded during underwater pile driving projects in several states. The database provides detailed information on pile and hammer types and sizes, site conditions, measured sound pressures, and attenuation data where applicable.

Appendix IV of the Guidance Manual contains an important "Agreement in Principal" for interim criteria for injury to fish from pile driving. Signed by the various agencies in 2008, the working group agreed to interim criteria as outline at the bottom of Table 2. The criteria include a peak sound pressure level (SEL) of 206 dB for all fish and a cumulative SEL level of 187 dB for fish 2 grams or heavier and a cumulative SEL of 183 dB for fish smaller than 2 grams.

***Table 1**. Pile driving studies demonstrating thresholds to damage during pile driving and recommended threshold.*

| Pile driving | Impact | Fish mass | $SPL_{pk}$ dB re 1 micro-Pascal | SEL dB re 1 micro-Pascal squared times seconds | $SEL_{cum}$ dB re 1 micro-Pascal squared times seconds |
|---|---|---|---|---|---|
| Popper et al. 2006 | Stunning | | | | 220 |
| | mortality | | | | 250 |
| Carlson et al. 2007 | Tissue damage threshold | < 0.5 g | | | 183 |
| | | > 200 g | | | >213 |
| Popper et al. 2007 | Auditory tissue damage | | 206 | | 189 |
| FHWG (2009) | Injury threshold recommendations only | All sizes of fish | 206 | | |
| | | ≥ 2 g | | | 187 |
| | | < 2 g | | | 183 |

# CHAPTER 8 - PROJECT PLANNING, PERMITTING, AND MANAGEMENT

FHWA construction projects occurring in or adjacent to sensitive habitats are subject to extensive environmental review during planning and permitting phases. Permits may be required from local, state, and federal agencies to ensure that impacts are avoided, minimized or mitigated. Extensive stipulations and requirements can be imposed on projects before ground work actually begins. Pre-construction planning time for permitting can easily increase the construction time by 10-fold if pre-planning communications do not address agency concerns.

To expedite the planning and permitting process, it is critical to understand the issues and concerns that federal and state agencies face with respect to carrying out laws and regulations that affect blasting projects. In the authors' experience, conflicts and delays arise for many foreseen and unforeseen reasons of which the following is a partial list:

- Project design teams are not prepared to address many of the misunderstandings that blast effects are thought to have on aquatic environments and are not prepared to negotiate or offer mitigating measures prior to the final design;
- conflicts arise among agencies that take time to resolve; the resolution processes may be out of the hands of project owners and design engineers;
- environmental assessments for locally or federally protected species can be lengthy and controversial; and
- many game and fish agencies have standard stipulations and conditions they apply to blasting projects; if these conditions are satisfied early on, the permitting process is likely to take less time.

The following sections will summarize some of the current regulatory requirements and permits necessary for blasting projects in or near fish habitat. In addition, best management practices (BMPs) and examples of project permits and specifications will be discussed as they apply to fish and fish habitat, as well as community members and special interest groups.

## 8.1 REGULATORY PERMITTING REQUIREMENTS

Several permits and approvals are necessary for blasting projects and each application may require different planning documentation for review and approval. At a federal level, blasting permits often require permits from the U.S. Army Corps of Engineers (Corps) for dredging or filling waters under the Clean Water Act Section 404. The Corps must consult with the U.S. Fish and Wildlife Service (USFWS) and National Marine Fisheries Service (NMFS) of the National Oceanic and Atmospheric Administration (NOAA) in such matters. These agencies are responsible for ensuring that development projects comply with the Magnuson-Stevens Act of 1976, the Endangered Species Act 1973 (ESA), and the Marine Mammal Protection Act of 1972. The Magnuson-Stevens Act requires that impacts to essential fish habitat (EFH) are minimized. NOAA and USFWS review projects for the potential harassment, injury or killing (generally referred to as "take") of ESA listed species or adverse modification of critical habitat. Stipulations or conditions may be applied to projects for compliance with these Acts.

State resource agencies, including departments of natural resources and game and fish divisions, may require review and permits for projects that may impact coastal zones, water ways, species, and habitats. In some states these authorities are shared with local governments including city councils and Coastal Zone Management Act (CZMA) appointed agencies. In all cases, reviews, permits, and conditions are specific to the region where projects will occur. Conditions and stipulations for blasting projects may vary from region to region or project to project based on the infrequent number of blasting projects near marine resources and the obscurity of supporting information.

## 8.2 STATE RESOURCE AGENCY REQUIREMENTS

State resource departments responsible for managing game and fish resources issue permits for projects involving blasting near fish and fish habitat. Representative agencies were contacted and asked how blasting projects are reviewed and permitted. Examples from four western states and Canada are summarized below. More examples for specific projects can be found in Appendix B.

The information contained herein is not necessarily complete. The information does, however, provide examples of the kinds of permits required at the time of this white paper completion.

### 8.2.1 California

The California Department of Fish and Wildlife (CDFW) requires notification of proposed projects that may alter rivers, streams, or lakes. Proposals are reviewed and if CDFW determines an activity will affect fish or wildlife resources, Lake or Streambed Alteration Agreements containing conditions or stipulations are issued. For blasting projects, mitigation measures and stipulations are based on avoidance techniques and have included isolating work areas and removing fish.

### 8.2.2 Oregon

The Oregon Department of Fish and Wildlife (ODFW) works with project planners during the application period to address fish passage issues and potential mitigation measures. ODFW maintains a website that posts in-water timing guidance to minimize impacts to fish during in-water work and blasting permit applications. General conditions applied to blasting permits include minimizing disturbance of stream banks and streamside vegetation by reseeding disturbed soils, a clause for compensation of damaged fish if determined necessary by ODFW, and removing blasting debris (shock tube, boxes, etc.) from the area immediately after the blast. Special conditions are determined for each project and can include work windows, the use of delays, isolating and dewatering work areas, and removing fish prior to work.

### 8.2.3 Washington

The Washington Department of Fish and Wildlife (WDFW) is mandated to protect fish from impacts created by hydraulic projects that use, divert, obstruct, or change the natural bed or flow of state waters. Mitigation requirements in Hydraulic Project Approvals (HPA) designed to reduce project impacts are project specific and can include the use of delay timing, removal of blast material and debris from streams, notification of fish kills, obtaining a diver for damage assessment, flow restrictions and work windows, use of blast mats and bubble curtains, isolation of work area, and fish removal.

### 8.2.4 Alaska

The Alaska Department of Fish and Game (ADFG) Division of Habitat is responsible for reviewing and permitting projects that may impact fish, habitat, and fish passage. Fish Habitat Permits may be required for any blasting activity that occurs in or adjacent to fish bearing water bodies. ADFG provides a Blasting Standard for the Proper Protection of Fish on their website that provides suggestions to avoid and minimize impacts to fish. The suggestions include work windows, removing fish from the work area, avoiding working during sensitive life stages, controlled blasting techniques, restoring damaged habitat, and removing explosive debris from the worksite. If impacts cannot be avoided or minimized, overpressure and vibration monitoring may be required. Instantaneous pressure rises must remain below 7.3 psi (50 kPa) where fish are present and peak particle velocities are limited to no more than 2.0 in/s (51 kPa) during early stages of embryo incubation. If monitoring indicates pressure or vibration criteria have been exceeded, the regulating agency determines the next course of action on a case by case basis.

### 8.2.5 Canada Department of Fisheries and Oceans

The Canada DFO is responsible for protecting and conserving marine, intertidal and freshwater fisheries resources and follows the *Guidelines for the Use of Explosives In or Near Canadian Fisheries Waters* (Wright and Hopky 1998). The Guidelines contain mitigation methods, maximum allowable pressure and vibration limits, setbacks and equations that have been widely referenced throughout the United States in both literature and project conditions. Representatives from the Pacific and Northwest Territory DFO offices were contacted regarding application of the Guidelines; their responses are summarized below.

The DFO Pacific Region Fisheries Protection Program reviews activities involving blasting in and near water bodies in British Columbia and the Yukon Territory. Requirements for blasting projects often include best management practices such as the requirement for an environmental monitor to be present at the work site (Eric Chiang, DFO Fisheries Protection Biologist, personal communication, June 12$^{th}$, 2013). Other methods or practices may be recommended based on the Guidelines which can be found on the DFO website. The Guidelines set maximum allowable PPV (0.5 in/s, 13 mm/s) and overpressure limits (14.5 psi, 100 kPa) discussed previously. Additional methods that may be incorporated into projects include discouraged use of unconfined explosives, using angular stemming gravels 1/12$^{th}$ the diameter of bore holes, recover explosive debris after each blast, and prohibiting the use of ammonium nitrate fuel oil mixtures in or near water due to production of toxic by-products (ammonia).

The Northwest Territories DFO frequently receives proposals for seismic exploration activities using explosives. Biologists in the region suggest limiting instantaneous pressure change to 7.3 psi (50 kPa) to protect fish from blasting (Pete Cott, personal communication, June 13$^{th}$, 2013). The rationale for this level was taken from Godard et al. 2008 and discussed in the previous section. DFO biologists determined that the PPV setback distances and equations provided in the Wright and Hopky (1998) were not accurate and varied greatly between projects (Cott and Hanna 2005). Instead they recommend pressure and vibration monitoring to determine site-specific setbacks (Bruce Hanna, personal communication, June 14$^{th}$, 2013) to ensure PPVs remain below 0.5 in/s (13 mm/s) where embryos are present.

## 8.3 PRE-CONSTRUCTION PLANS AND SUBMITTALS FOR BLASTING

Bid documents specify requirements for blasting and monitoring plans that include limits placed on all ground vibration and water overpressures. It is the authors' opinion that specifications should be performance-based and not method-based. All too often specifications are written in consultation with experts that do not fully understand the complications that method-based restrictions can have on the end results. Specifying restrictions placed on the drilling and blasting design and explosives products can create adverse safety issues, excessive costs, and poor performance. Method-based monitoring plans have, in the past, specified unusual or incorrect procedures and equipment that do not represent best practices. Such restrictions can increase risk exposure and shift this risk to the design engineers and project sponsors.

### 8.3.1 Blasting plans

In most cases two types of blasting plans are required. The first is a comprehensive plan that applies to all blasts throughout the project in a general sense. The second type is the individual blasting plan that provides site specific details for each blast.

The general blasting plan provides personnel qualifications, resumes, and licenses of the blaster in charge, drilling and blasting crews, and third party blasting consultants; a list of all federal, state and local regulations to which the project must comply, copies of all permits; and detailed descriptions including MSDS sheets of all explosives materials, provisions for safe transportation, storage, handing, loading and disposal of packaging materials of all products to be used for blasting. The blasting contractor is responsible for obtaining all blasting permits for the job.

The general blasting plan must contain a safety plan that details personnel responsibility and safety during explosives transportation, storage, blast hole loading at the site, pre-blast and post-blast notifications, warning sirens, guarding of the site to prevent unauthorized access, and the return of unused explosives after the blast is completed. The location of all buried utilities are also the responsible of the blasting contractor.

The notification process includes all law officers with oversight, emergency personnel, and, in the case of underwater blasting on navigable waters, the coast guard and pilots. Residents and property owners within a pre-defined boundary of influence must also be included in the notifications along with warning signs posted on public and private roads explaining about the blasting process and siren patterns.

The general blasting plan shall detail at a minimum the following:

- explosive type, product name and size, weight per unit, and density
- delay type, sequence, and delay
- use of non-electrical or electronic initiation systems for all blasting operations
- stemming material quality and quantity and tamping method
- hole depth, diameter, and pattern
- explosive depth, distribution, and maximum charge and weight per delay

- number of holes per delay
- dates and hours of conducting blasting
- distance and orientation to nearest above ground structures and waterway features
- distances and orientations to the nearest underground structures, including pipelines and utilities
- safety procedures for storing, handling, transporting, loading, and firing explosives; fire prevention; inspections before and after each blast; misfires, flyrock and noise prevention; stray current accidental-detonation prevention; signs and flagmen; warning signals prior to each blast; exclusion zone distances for navigable waterways; all notifications and to whom issued prior to blasting, and disposal of waste blasting material
- copies of all required federal, state, and local permits
- blasters name, company, copy of license, and statement of qualifications
- magazine type and locations for explosives and detonating caps
- typical rock type and geology structure (solid, layered, or fractured)
- a Notification Plan for each blast
- plan and cross-section view of a typical blast of each type required (production, pre-split, controlled, underwater)

The individual blasting plan makes reference to the general blasting plan. However, this plan includes blast hole loading diagrams of explosive products, a plan view of the drilled hole pattern, and delay timing design. In some cases the estimated ground vibration or water overpressure at a specified distance from blasting are required.

### 8.3.2 Monitoring plan

Many project require a separate monitoring plan that describes instrumentation, deployment, analysis, and reporting of overpressures and vibrations. Monitoring for the protection of aquatic species can help ensure that required limits are not exceeded. Site-specific attenuation studies performed with a test blasting program early on can be used to optimize blasting and reduce excess pressures and vibrations. Resource managers can use attenuation models to make distance-energy predictions and determine a zone of impact. The monitoring plan will detail the following:

- monitoring company, names of equipment operators and those responsible for data analysis and reporting with resumes and qualifications
- equipment make and models, and operation parameters to comply with any specifications
- planned locations of monitoring equipment geophone and hydrophone
- calibration certificates
- examples of past reports
- provisions for pre- and post-blast surveys of all structure within the zone of influence

### 8.3.3 Community relations plans and outreach education programs

Construction projects that include rock blasting require a well-managed team of experts and consultants to guide the planning process and develop a comprehensive community relations plan. Blasting in itself is perceived to be destructive and often associated with primitive methods and products that render blasting as an uncontrollable process. The negative public opinion about underwater blasting and rock removal close to rivers and lakes is often shared by resource agencies and regulators who assume blasting cannot occur without detrimental impacts to fish and fish habitat.

One important objective in any public relations program is to make community members comfortable and receptive to learning the facts about the blasting project by identifying with their concerns and answering questions important to them. The best practice is to anticipate all possible questions about blasting impacts on property and the quality of life within the community, and answer them honestly and objectively before the questions arise using the best science possible. In some cases blasting related questions may not be answered to the satisfaction of everyone. It is best to make provisions for follow up responses with further information at a later date.

There are several means to control the misconceptions and negative opinions about large construction projects that may be administered throughout the planning and permitting stages to help the process reach construction in a timely manner. These include written materials and in-person communication. Various media and forums for communication are as follows:

- Written materials, flyers and handouts to be used at meetings to present and discuss the facts, benefits and general plans for the project, and answers to anticipated concerns.
- A well-crafted "blasting facts" document or brochure with contact names and phone numbers; the document must emphasize the protection programs in place for monitoring and reporting.
- Personal contacts and meetings with key community members and special interest groups to discuss concerns.
- Proactive, informational meetings to present the project and address concerns in a controlled, well-planned atmosphere in which the consultants and PR staff maintain control.
- Develop an informational web site and set up a hot line for questions and concerns to be directed to the appropriate personnel for answers.

In dialog with the community, emphasis must be placed on control measures in place that protect nearby property and resources in compliance with all applicable regulations.

## 8.4 PROJECT IMPLEMENTATION: BEST MANAGEMENT PRACTICES (BMPS)

Alternative construction methods for which blasting may be one alternative are often considered during the initial impact assessment period. Examples of projects where blasting was found to be the best alternative for rock removal are given in Appendix C.

Best management practices (BMPs) dictate that all conservative measures for blast risk mitigation are continually followed, monitored and documented. It is important to keep in mind many of the best practices that improve the efficiency of a blasting project may also minimize unwanted effects on surrounding environments and reduce project costs.

BMPs for the blasting industry are dictated by professional and industry organizations who promote safe practices. Examples include:

- The International Society of Explosives Engineers (ISEE) promotes the standardization of methods in explosives engineering as well as the professional development, competence, and qualifications of those in the field.
- The Institute of Makers of Explosives (IME) participates in the development of industry standards and best practices and publishes recommendations and guidelines for all facets of explosives operations as Safety Library Publications (SLPs). Best practices include a wide array of methods and techniques to improve blast efficiency, ensure safety, and minimize unwanted effects.

Several recent marine and freshwater project specifications were reviewed for common blasting practices that could minimize blasting impacts on fish and fish habitat and improve public confidence. Many of the following practices listed below are considered as standards for marine blasting projects:

- employ qualified blasting specialists and blaster-in-charge;
- obtain the services of the best blasting consultants possible with public relations and agency negotiation skills;
- use explosives designed for marine environments and recover all waste materials after blasting from the water;
- perform a test blasting program prior to operational blasting to allow agency oversight and reviews, develop optimum blast designs and establish attenuation models for vibration and water overpressures; attenuation models can then be used in the “feed-back” for blast design to ensure off-site impact limits are met;
- use controlled blasting techniques at all times with accurate drilling and precise hole loading practices;
- maintain detailed records of drilling in the form of drill logs and blasting hole loading logs for post-blast reporting;
- maintain contingency plans for misfires and spills;
- submit detailed reports and records for each blast;
- data base management system for the safe storage and easy retrieval of blasting and monitoring records and measurements including water quality, fish surveys, watch zone results and any post-blast “takes”; and
- secure storage of all photographs and videos of pre-construction conditions, during and post-blast conditions.

Good community relations during project implementation require that the following are in place:

- a comprehensive blast-related complaint response plan to document and respond to complaints so that the complaints are fully attended to and closely monitored to arrive at a quick and mutually agreeable resolve; and
- a means for internal communication and project updates to all contractors and PR staff to understand the progress of the blasting process and how risks are being continually mitigated.

### 8.4.1 The use of consultants

Third-party consultants who specialize in the management of blasting risks, working for either the project owner or the general contractor, are invaluable to construction projects. Blasting risks include such things as unintended or premature detonations, flyrock, and excessive vibrations or water overpressures. Risk management requires the following four basic elements of safe blasting:

- proper blast design,
- specifications,
- pre-qualifications, and
- oversight during blasting operations.

The use of well-qualified blasting consultants working on behalf of the owner to manage blast-related risks and verify safe blasting practices on projects can save time and money. *Contracting to blasting consultants and specialists who have demonstrated expertise in similar projects is by far the best practice for project owners when internal expertise is not available and third party verification is needed*.

Third-party verification by consultants can be beneficial in the following areas:

- Preparation of permits and impact statements;
- Pre-construction negotiations when certain compliance guidelines are missing in the project specifications or guidelines are unduly onerous or misapplied;
- Public relations to instill confidence in the affected public, to emphasize project benefits, and reassure that the project will present only temporary inconvenience and will be well-managed and controlled;
- Pre-site impact assessment such as unforeseen issues and document existing conditions;
- Approval of blast designs or operational characteristics of vibration-producing equipment;
- Monitoring of vibration and water overpressures, and
- Approval of blast reports and monitoring results demonstrating compliance with permit requirements, specifications, or regulations.

### 8.4.2 Managing permit conditions

***A. Allowable Take***

Allowable take limits are determined by the appropriate regulating agencies during the permitting process. Take limits are often determined through consideration of established zones of impact and pre-determined thresholds of mortality, injury, or harassment. Limits can be set for a single event or entire project.

In order to determine if take limits have been exceeded, impacts must be documented after each blast. For instance, mortality counts can be performed immediately after a blast by trained personnel that capture or visually observe dead fish. Injury and harassment are more difficult to observe in field conditions and are subject to observer interpretation.

When physical capture or observation are not possible, take can be estimated through modeling and survey techniques. Acoustic surveys can be used to determine fish density in an area and approximate the probable number of a fish exposed to blast effects in that area. If pressure and vibration limits are established for mortality, injury, or harassment, prediction formulas are then used to estimate the take in a given zone of impact.

***B. Compensation and fines***

When impacts cannot be avoided or minimized, monetary compensation or restitution may be required. Monetary compensation values can be based on actual counts of dead fish, projected numbers of fish mortality, or other methods determined by the regulating authority.

(blank page)

# CHAPTER 9 - EXAMPLES OF AQUATIC BLASTING PROJECT SPECIFICATIONS

Three recent marine blasting project specifications and requirements were reviewed for methods and techniques designed to mitigate the impact of blasting on fish and fish habitat. The specifications represent a comprehensive description of requirements and objectives necessary to complete the projects within the scope of permits provided by federal, state, and local agencies. The projects and mitigation methods are summarized below.

**Project:** *Columbia River Channel Improvements (CRCI)*, Columbia River, Columbia County, Saint Helens, Oregon and Clark County, Washington. (2009-2010).

- Use controlled blasting techniques including a test blasting plan, limit the maximum charge weight per delay, use adequate stemming materials, apply drill hole diameter limitation, detailed methods for positioning shots and drill holes
- All drilling and blasting procedures and equipment shall minimize effects on material beyond the project boundary
- Spill prevention and containment plan
- Recover all exploded shock tube from water
- Safety zone and watch program in place for endangered species and marine mammals
- Incidental take limits of no more than 10 adult and 50 juvenile ESA listed salmon
- Timing restrictions to protect fish
- Maximum peak pressure limit specified, suspend blasting if limit exceeded
- Minimum specifications for pressure monitoring equipment

**Project:** *Wilmington Harbor Deepening Anchorage Basin*, New Hanover and Brunswick Counties, North Carolina (2012).

- Use controlled blasting techniques including a test blasting plan, maximum charge weight per delay, stemming requirements, detailed methods for positioning shots and drill holes
- Spill prevention and containment plan
- Recover all exploded shock tube from water
- Detonate scare charges prior to each blast
- Safety zone and watch program
- Set gill nets before and after blasting to monitor fish presence and catch injured or killed fish post blasting
- Perform sonar sweeps of blast area, halt blasting if schools of fish are present
- Timing restrictions to protect fish
- Maximum peak pressure limit specified, suspend blasting if limit exceeded
- Minimum specifications for pressure monitoring equipment

**Project:** *Cushman Dam No. 2 Fish Collection/Sorting Facility and North Fork Skokomish Powerhouse*, City of Tacoma, Washington (2011).

- Use controlled blasting techniques including a test blasting plan, stemming requirements, detailed methods for positioning shots and drill holes

- All drilling and blasting procedures and equipment shall minimize effects on material beyond the project boundary
- Spill prevention and containment plan
- Timing restrictions to protect fish
- Physically separate blasting from water body if possible
- Maximum peak pressure limit specified for areas where fish may be present
- Maximum peak vibration limit where fish embryos may be present
- Suspend blasting if specified pressure or vibration limits are exceeded
- Minimum specifications for pressure and vibration monitoring equipment

All three above projects required in-water pressure monitoring during blasting activities to comply with the limits imposed at monitoring locations specified in Table 3. Minimum specifications for monitoring equipment differed between projects. CRCI and Wilmington Harbor required similar types of equipment capable of recording peak pressures 0 to 1,000 psi (6895 kPa) and sampling at 500 kHz. The Cushman Dam project required equipment capable of recording up to 47 psi (324 kPa) at a sample rate of 65 kHz.

***Table 2***. *Marine blasting project specifications for overpressure monitoring. Maximum allowable overpressures (psi) and monitoring locations are listed for three projects.*

| Project | Monitoring Location | Maximum Allowable Pressure (psi) |
|---|---|---|
| Columbia River Blasting, OR | 140 ft from blast | cautionary 40<br>maximum 70 |
| Wilmington Harbor, NC | 140 ft from blast | 120 |
| Cushman Dam, WA | where fish may be present | 2.7 |

# CHAPTER 10 - CONCLUSIONS AND RECOMMENDATIONS

This White Paper addresses the generation and transmission of blast energy and the effects that overpressures and vibrations can have on fish and fish habitat. Management challenges that arise when planning and executing blasting projects are discussed. Scientific studies correlating blasting with impacts to fish and recommended guidelines that limit vibrations, overpressures, and sound pressure levels were reviewed. An overview of mitigation techniques and examples of successful projects are presented. Throughout the Paper, emphasis is made in areas where further research and standardized methods are needed.

## 10.1 CONCLUSIONS

### 10.1.1 Metrics and measurement systems used to explain fish damage

An evaluation of literature on construction and blast effects on fish clearly indicated there are gaps in the pressure and sound metrics used to define impacts to fish from exposure to blast induced vibrations and overpressures. Conclusions regarding metrics and measurements systems used to correlate fish damage and blasting are as follows:

- Units used to report underwater blast effects from blasting are not standardized and include different versions of overpressure calculations in terms of peak pressure (psi) and log transformations of pressure, in various units of sound pressure (decibels, dB).
- The process of log-transforming pressure measurements is not intuitive to most construction project managers, biologists, blasters, engineers and compliance personnel on rock removal projects. An advanced understanding of acoustics is needed when permit conditions and compliance reporting units are given in terms of sound pressure for construction and blasting near water bodies.
- There is no consistent method by which blasting impulse is measured and converted to sound pressure which leads to confusion when evaluating published measurements and criteria used by agencies to protect fish.
- Sound pressure can be described in many different ways (average, peak, cumulative, and impulse levels), each with a unique formula and time interval over which pressure is integrated. It is unclear which metric best correlates with fish injury from blasting.
- Many of the signal processing algorithms used to quantify and mitigate noise exposure for continuous sources such as pile driving, rock hammering, and so forth, do not necessarily apply to blasting; the impacts on fish from continuous pressure pulses lasting several minutes are not the same as the impacts from a transient blasting impulses lasting a fraction of one second.
- Although the effects of some sound pressure and vibration sources on fish have been studied, the limited findings cannot be meaningfully applied to all construction activities or fish species.

### 10.1.2 Blasting effects on fish

Impacts to fish from blast induced pressure changes are affected by many variables including but not limited to, fish species, physiology, life history, size, maturity, and physical factors such as position in the water column. Barotrauma injuries to fish as a result of blasting have not been widely studied and are not well understood by regulating agencies or the construction industry.

The following conclusions are made with respect to blast effects on fish:

- Several studies have attempted to correlate explosive source energy with distances and fish injury; however, there are many uncontrollable variables that prevent useful correlations to set meaningful limits.
- There is little or no data available on the attenuation or decay of blast overpressures with distance from the source in or near water to rely upon for prediction and mitigation.
- Physiological and behavioral effects on fish are difficult to quantify as specimens are not easily observed in their natural habitats during or soon after blasting.
- There is no agreed upon injury classification system to assess post-blast exposure conditions of fish; in many cases, the exact method or system of injury classification is not detailed in research reports and publications and the level of injury that is considered lethal is unclear.
- The body of scientific and commercial data currently available appears to be inadequate for the purpose of developing more than the most preliminary scientifically supported criteria that will protect fish from exposure to blast induced overpressures.

### 10.1.3 Mitigation

- Many of the best practices that improve the efficiency of a blasting project may also minimize unwanted effects on surrounding environments and reduce project costs.
- Some mitigation measures that are successful for pile driving such as the use of cofferdams and bubble curtain, are ineffective in mitigating underwater blasting overpressures in certain conditions.
- Meaningful mitigating measures are often overlooked during the planning phase of projects and absent from some specifications.

### 10.1.4 Project planning

- Blast effects on aquatic environments are often misunderstood in the design phase of projects.
- Environmental assessments for locally or federally protected species when blasting takes place can be lengthy and controversial, resulting in possible project delay;
- Many game and fish agencies have standard stipulations and conditions applied to blasting projects; if these conditions are known by designer engineers and satisfied early on in the permitting process, it is likely that the planning phase may take less time; and
- Conflicts among project stakeholders arise from misunderstandings that blast effects can be detrimental to aquatic environments.

## 10.2 RECOMMENDATIONS

In order to effectively manage blasting projects in or near fish habitat, systematic studies are needed to quantify the effects of blasting and construction vibrations and overpressures. Such studies need to extend the relationships between pressure metrics and fish size and safe stand-off distances for all fish species of interest. Any correlations of the pressure metric with sound exposure levels must include a relevant computation method for SEL that applies to all fish species over the pressure-time interval of the transient source.

Some of the areas and concepts identified in this white paper that need further research and discussion are summarized below.

- Compare blast impact metrics in terms of pressure (impulse, peak pressure, and others) and their usefulness in terms of attenuation models to predict the effects on fish with distance.
- Clarify and standardize any relevant correlations between pressure metrics and sound exposure calculations.
- Develop attenuation models of overpressures for blasting (different confinement levels, beneath water bodies, in water, adjacent to water, various shot sizes, etc.) for different conditions (still deep water, flowing water, shallow water, attenuation near the surface, mid-water or bottom, etc.).
- Evaluate the transmission of ground vibrations to water overpressure at the ground/water interface when land blasting adjacent to water.
- Distinguish between blasting and non-blasting activities; criteria developed for other activities (pile driving, air guns, heavy equipment) cannot be applied to blasting.
- Develop monitoring guidelines to include the position of equipment in the water column and relative to the blast (scaled and actual distance), minimum equipment specifications, information to be reported, and so forth.
- Identify key managed species affected by blast overpressures; there are many species of fish all with different physiology, distributions, life histories, and damaging impact levels.
- Perform more field studies on the effects of blast vibrations on incubating embryos.
- Assure methods of assessing impacts to fish are clearly stated, and fish injury are clarified and standardized if possible; knowing what injury levels are considered lethal could help assess take limits and field take counts.
- Identify what pressure and vibration levels and parameters of blast strength cause injury and mortality in fish; comparison studies must be limited to those performed under similar, controlled conditions; for all studies it is imperative to include monitoring methods and locations, equipment specifications, and calculation methods in reports.
- Develop guidance criteria and project specifications as they pertain to fish injuries for blasting operations occurring in and near water bodies.
- Examine the effectiveness and feasibility of mitigation measures for all construction activities.

- Require general contractors to submit general and individual blasting plans as well as a comprehensive monitoring plan to include provisions for fish protection and provide evidence that all limits adopted for the project will be met by the proposed blast designs.
- Standardize means of implementing the permitting process in a timely manner and improve inter-agency relations to address concerns early in project planning phases; federal and state agencies responsible for fish protection must be included in the project planning process.
- Require a test blasting phase for all projects to ensure impacts to fish may be controlled.
- Include the services of a qualified blasting consultant and a fisheries consultant early in the design phase of projects to expedite compliance with the permitting process; such specialists can suggest modifications to blast designs and a monitoring program to comply with recommended criteria limiting overpressures, vibrations, and sound pressure levels.

## REFERENCES

Alaska Department of Game and Fish (ADFG). 1991. ADFG blasting standards for the protection of fish. Draft Report.

Baxter, L., E. E. Hayes, G. R. Hampson, and, R. H. Backus. 1982. Mortality of fish subjected to explosive shock as applied to oil well severance on George's Bank. Woods Hole Oceanog. Inst. Tech. Rept., WHOI-82-54. Prepared for the Technology Assessment and Research Program of the Minerals Management Service, Dept. of the Interior.

California Department of Transportation (Caltrans) 2009. Technical guidance for assessment and mitigation of the hydroacoustic effects of pile driving on fish. Prepared by: ICF Jones & Stokes. Sacramento, CA and Illingworth and Rodkin, Inc., Petaluma, CA.

Carlson, T., M. Hastings, and A. N. Popper. 2007. Update on recommendations for revised interim sound exposure criteria for fish during pile driving activities. Memorandum to Suzanne Thesis (California Department of Transportation) and Paul Wagner (Washington Department of Transportation).

Carlson, T., G. Johnson, C. Woodley, J. Skalski, and, A. Seaburg. 2011. Compliance monitoring of underwater blasting for rock removal at Warrior Point, Columbia River Channel Improvement Project 2009/2010. Pacific Northwest National Laboratory Completion Report (PNNL-20388), Prepared for the U.S. Army Corps of Engineers.

Casper, B. M., A. N. Popper, F. Matthews, T. J. Carlson, and, M. B. Halvorsen. 2012. Recovery of barotrauma injuries in Chinook salmon, *Oncorhynchus tshawytscha* from exposure to pile driving sound. PLOS ONE 7(6):e39593.

Clean Water Act of 1972. 33 USC 1251 et seq.

Cole, R. H. 1948. Underwater explosions. Princeton University Press, Princeton, NJ.

Cott, P. A., and, B. W. Hanna. 2005. Monitoring explosive-based winter seismic exploration in waterbodies, NWT 2000-2002. Pages 493-510 *in* Offshore Oil and Gas Environmental Effect Monitoring: Approaches and Technologies. Battelle Press.

Dowding, C. H. 2002. Construction vibrations. Prentice Hall.

Faulkner, S. G., W. M. Tonn, M. Welz, and, D. R. Schmitt. 2006. Effects of explosives on incubating lake trout eggs in the Canadian Arctic. North American Journal of Fisheries Management 26(4):833-842.

Faulkner, S. G., M. Welz, W. M. Tonn, and, D. R. Schmitt. 2008. Effects of simulated blasting on mortality of rainbow trout eggs. Transactions of the American Fisheries Society 137:1-12.

Fernet, D. A. 1982. The effects of underwater detonation of explosives on caged fish in the Bow River, Alberta. Environmental Management Associates, Calgary. Prepared for the Alberta Section of the Alaska Highway Gas Pipeline Project.

Fisheries Hydroacoustic Working Group (FHWG). 2008. Agreement in principal for interim criteria for injury to fish from pile driving activities. Memorandum dated June 12, 2008. Available online at: http://www.dot.ca.gov/hq/env/bio/files/fhwgcriteria_agree.pdf.

Fisheries Hydroacoustic Working Group (FHWG). 2013. Underwater noise monitoring template. Template posted November 22, 2013. Available online at: http://www.dot.ca.gov/hq/env/bio/fisheries_bioacoustics.htm.

Froese, R. and D. Pauly. Editors. 2013. Fishbase. Available: http://www.fishbase.org, version (12/2013).

Fitch, J. E., and P. H Young. 1948. Use and effect of explosives in California coastal waters. California Department of Fish and Game 34, no. 2: 53-70.

Gaspin, J. B., M. L. Wiley, and, G. B. Peters. 1975. Experimental investigations of the effects of underwater explosions on swimbladder fish, I: 1973 Chesapeake Bay Tests, NSWC TR 75-78. Naval Surface Weapons Center, Silver Spring, MD.

Godard, D. R., L. Peters, R. Evans, K. Wautier, P. A. Cott, B. Hanna, and, V. Palace. 2008. Histopathological assessment of the sub-lethal effects of instantaneous pressure changes (IPCs) on rainbow trout (*Onchorhynchus mykiss*) early life stages following exposure to detonations under ice cover. Environmental Studies Research Funds, Report No. 164, Winnipeg.

Goertner, J. F., M. L. Wiley, G. A. Young, and, W. W. McDonald. 1994. Effects of underwater explosions on fish without swimbladders, NSWC TR 88-114. Naval Surface Warfare Center, Silver Springs, MD.

Govoni, J. J., Settle, L. R., and West, M. A. 2003. Trauma to juvenile pinfish and spot inflicted by submarine detonations. J. Aquatic Animal Health 15(2):111-119.

Govoni, J. J., M. A.West, L.R. Settle, R.T. Lynch, and M. D. Greene. 2008. The effects of underwater explosions on larval fish: implications for a coastal engineering project. Journal of Coastal Research 24(sp2):228-233.

Grogan, A. 2005. Design and testing of a bubble curtain at Whirl Bay, BC. International Society of Explosives Engineers 2005:1-11.

Hastings, M.C., and A. N. Popper. 2005. Effects of sound on fish. Under contract to Jones & Stokes, Sacramento, CA. California Department of Transportation Contract No. 43A0139, Task Order 1.

Hempen, G. L. 1993. Reducing underwater blast damage with air-screens. Nineteenth Annual Conference on Explosives and Blasting Technique 19:337-346.

Houghton, J. P., and, D. R. Munday. 1987. Effects of linear explosive seismic energy releases on fish in Alaska's transition zones. Final Report, 06793-004-020. Prepared for the Alaska Oil and Gas Association.

Hubbs, C. L., and, A. B. Rechnitzer. 1952. Report on experiments designed to determine effects of underwater explosions on fish life. California Fish and Game 38(3):333-366.

International Society of Explosives Engineers (ISEE). 2009. ISEE field practice guideline for blasting seismographs. 2009 Ed. International Society of Explosives Engineers, Cleveland, OH (http://www.isee.org/media/pdf/FieldPracticeGuidelinesRev03_01_10.pdf).

International Society of Explosives Engineers (SEE). 2011. Performance specifications for blasting seismographs. International Society of Explosives Engineers, Cleveland, OH. (http://www.isee.org/images/stories/pdf/perfspec2_14_11.pdf).

Jensen, J. O. T., and, D. F. Alderdice. 1983. Changes in mechanical shock sensitivity of coho salmon (*Oncorhynchus kisutch*) eggs during incubation. Aquaculture 32(3):303-312.

Jensen, J. O. T., and, D. F. Alderdice. 1989. Comparison of mechanical shock sensitivity of eggs of five Pacific salmon (*Oncorhynchus*) species and steelhead trout (*Salmo gairdneri*). Aquaculture 78(2):163-181.

Kearns, R. K., and, F. C. Boyd. 1965. The effect of a marine seismic exploration on fish populations in British Columbia coastal waters. Canadian Fish Culturist 34:3-26.

Keevin, T. M., and G. L. Hempen. 1997. The environmental effects of underwater explosions with methods to mitigate impacts. U.S. Army Corps of Engineers, St. Louis District.

Knick Arm Bridge and Toll Authority. 2006. Knik Arm crossing: final underwater measurements of pile-driving sounds during the Port MacKenzie dock modifications. 13–16 August, 2004. Agreement No: P 42070 Federal Project No: ACSTP-0001(277). AKSAS Project No: 56047.

Knudsen, F., P. Enger, and, O. Sand. 1992. Awareness reactions and avoidance responses to sound in juvenile Atlantic salmon (*Salmo salar*). Journal of Fish Biology 40(4):523-534.

Kolden, K. D. and C. T. Aimone-Martin. 2013. Blasting effects on salmonids. Contract IHP-13-051. Prepared for the Alaska Department of Fish and Game, Division of Habitat, Douglas, AK.

Magnuson-Stevens Fishery Conservation and Management Act of 1976. 16 USC 1801, et seq.

Marine Mammal Protection Act of 1972. 16 USC Chapter 31.

Matuschek R. and K. Betke. 2009. Measurement of construction noise during pile driving of offshore research platforms and wind farms. NAG/DAGA /2009, Rotterdam, pp. 262-265.

McAnuff, L. A., and, R. T. Booren. 1989. Fish mortality study during underwater blasting operations in Lake Erie off Nanticoke, Ontario. International Society of Explosives Engineers 1989:131-143.

McAnuff, L. A., M. V. van Bers, and A. Curic. 1994. Environmental effects of marine blasting in Canadia game rivers. International Society of Explosives Engineers 1994:479-490.

McCauley, R. D., J. Fewtrell, and, A. N. Popper. 2003. High intensity anthropogenic sound damages fish ears. The Journal of the Acoustical Society of America 113(1):638-642.

Munday, D. R., G. L. Ennis, D. G. Wright, D. C. Jeffries, E. R. McGreer, and, J. S. Mathers. 1986. Development and evaluation of a model to predict effects of buried underwater blasting charges on fish populations in shallow water areas. Can. Tech. Rep. Fish. Aquat. Sci., No. 1418, Vancouver, BC. Department of Fisheries and Oceans, Habitat Management Division.

Nedwell, J. R., Turnpenny, A. W. H., Lovell, J. M., and B. Edwards. 2006. An investigation into the effects of underwater piling noise on salmonids. Journal of the Acoustical

Society of America 120**:**2550–2554.

Popper, A. N., T. J. Carlson, A. D. Hawkins, B. L. Southall, and R. L. Gentry. 2006. Interim Criteria for Injury of Fish Exposed to Pile Driving Operations: A white paper.

Racca, R. G., D. E. Hannay, R. B. Murray, W. B. Griffiths, and, M. Muller. 2004. Testing fish deterrents for use under-ice in the Mackenzie Delta area. Environmental Studies Research Funds Report No. 145, Calgary. Prepared for the National Energy Board.

Richmond, D. R., T. Yelverton, and E. R. Fletcher. 1973. Underwater blast injuries produced by charges. Technical Progress Report. Washington, DC. Defense Nuclear Agency.

Ruggerone, G. T., Goodman, S. E. and R. Miner. 2008. Behavioral response and survival of juvenile coho salmon to pile driving sounds. Seattle, WA: Natural Resources Consultants, Inc. for Port of Washington. (http://home.comcast.net/~ruggerone/FishTerminal PileDriveStudy.pdf).

Simmonds, E. J., and, D. N. MacLennan. 2005. Fisheries acoustics: theory and practice, 2nd edition. Blackwell Publishing, Iowa.

Siskind, D. E. 2000. Vibrations from blasting, 1st edition. International Society of Explosives Engineers, Cleveland, OH.

Smirnov, A. I. 1954. The effect of mechanical agitation on developing eggs of the pink salmon (*Onchorynchus gorbuscha*, WALBAUM, Salmonidae). Doklady Akademii Nauk SSSR Vol. 97(2):365-368. Fish. Res. Bd. Canada Translation Series 231.

Smirnov, A. I. 1955. The effect of mechanical agitation in different periods of development on the eggs of autumn chum salmon (*Oncorhyncus keta* INFRASP. *autumnalis Berg*, Salmonidae). Doklady Akademii Nauk SSSR Vol. 105(4):873-876. Fish. Res. Bd. Canada Translation Series No. 230.

Southall, B.L. et al., A.E. Bowles, W.T. Ellison, J.J. Finneran, R.L. Gentry, C.R. Green Jr, D. Kastak, D.R. Ketten, J.H. Miller, and P.E. Nachtigall. 2007. Marine mammal noise exposure criteria: Initial scientific recommendations. Aquatic Mammals. Vol. 33(4).

Strach, R., M. Crouse, and T. Collier. 2006. NWFSC response to NWR and SWR request for assistance on interpretation of "Interim Criteria for Injury of Fish Exposed to Pile Driving Operations: A White Paper". Memo dated Sept. 19, 2006. Northwest Fisheries Science Center, National Marine Fisheries Service.

Sverdrup, A., E. Kjellsby, P. Krüger, R. Fløysand, F. Knudsen, P. Enger, K. Helle. 1994. Effects of experimental seismic shock on vasoactivity of arteries, integrity of the vascular endothelium and on primary stress hormones of the Atlantic salmon. Journal of Fish Biology 45(6):973-995.

Teleki, G. C., and, A. J. Chamberlain. 1978. Acute effects of underwater construction blasting on fishes in Long Point Bay, Lake Erie. Journal of the Fisheries Research Board of Canada 35:1191-1198.

Swisdak, Jr., M.M. 1978. Explosion effects and properties: Part II - Explosion effects in water. Naval Surface Weapons Center, Silver Spring, MD. NSWC/WOL TR 76-116.

Teleki, G. C., and, A. J. Chamberlain. 1978. Acute effects of underwater construction blasting on fishes in Long Point Bay, Lake Erie. Journal of the Fisheries Research Board of Canada 35:1191-1198.

Timothy, J. 2013. Alaska blasting standard for the proper protection of fish. Alaska Department of Fish and Game, Habitat Publication No.13-03, Douglas, AK.

Wartzok, D., J. Altmann, J., W. W. Au, K. Ralls, K., A. Starfield, P. Tyack, P., J. Bintz, J. Merrill, D. Greene, S. Capote, and N. Grossblatt. 2005. Marine Mammal populations and ocean noise: determining when noise cases biologically significant effects. National Academic Press, Washington DC.

Wiley, M. L., J. B. Gaspin, and, J. F. Goertner. 1981. Effects of underwater explosions on fish with a dynamical model to predict fishkill. Ocean Science and Engineering 6(2):223-284.

Wright, D. G., and, G. E. Hopky. 1998. Guidelines for the use of explosives in or near Canadian fisheries waters. Can. Tech. Rep. Fish. Aquat. Sci., No. 2107. Department of Fisheries and Oceans.

Yelverton, J. T., D. R. Richmond, W. Hicks, H. Saunders, and, E. R. Fletcher. 1975. The relationship between fish size and their response to underwater blast. Lovelace Foundation for Medical Education and Research Topical Report, DNA 3677T, Albuquerque, NM. Prepared for the Defense Nuclear Agency.

(blank page)

# APPENDIX A – SCOPING DOCUMENT SUBMITTED BY CENTRAL FEDERAL LANDS HIGHWAY DIVISION, FEDERAL HIGHWAY ADMINISTRATION (FHWA)

The following set of questions represent the Scoping Document prepared as a guide for the development of this White Paper. The questions, posed in 2013, are answered herein and provide a general overview of the issues of important to FHWA.

**Question1**

A) In general, what are the environmental issues surrounding construction vibration impacts to waterways?
B) Are they primarily limited to fish spawning and migration, or are other aquatic animals impacted as well?

*Although this paper focuses on fish, other aquatic species (invertebrates, birds, amphibians, mammals) can be affected. Destruction of habitat is also a concern.*

C) Are some types of fish and aquatic animals more susceptible than others (or at different times)?

*This paper focuses on fish. There are several physiological factors to consider such as size, age, reproductive maturity, and so forth. Section 4.0 addresses the adverse effects on fish from blasting and construction vibrations and explains this question in more detail.*

D) Is this a year-round problem, or are construction vibration impacts generally seasonal?

*For some species, impacts can be year-round and others, impact are dependent on seasonal life-cycles. Section 4.0 addresses this question in more detail.*

**Question 2**

A) What elements of construction vibrations are potentially harmful to fish or other aquatic life?

*Section 4.0 provides the types of injuries and alludes to some of the seismic characteristics that affects the injuries. In general, for both vibrations and water overpressures, the elements are amplitude or intensity of the disturbances, time duration of the pulses and the frequencies both at the peaks and over the entire waveform time histories (predominant frequencies).*

B) Are impacts primarily related to seismic amplitude, frequency content, duration or other transmitted energy factors?

*This is correct. However for water overpressures, federal and state agencies have historically transformed pressure transients to sound pressure and performed a number of mathematical manipulations of the time histories in an attempt to find a metric that correlates with hearing loss, injury and mortality (peak values, RMS, accumulations of energy, sound exposures, and energy flux density). In addition the time application of these metrics during the pressure transient is subject to debate.*

*We feel that these efforts have not been successful due to inherent measurement errors associated with too few samples, the lack of consistency in experimental design to take pressure or sound measurement at consistent spatial locations for the impulse sources, and the various stages and sizes fish represent in experimental studies that contribute to variabilities that cannot be quantified.*

**Question 3**

A) Are problematic seismic sources limited to blasting or are mechanical energy sources (e.g., pile driving, mechanical excavation, vibratory compaction) problematic as well?

*Pile driving is the non-blasting source that has been extensively studied and mitigation measurements have been somewhat successful for pile foundation driving projects. The repetitive nature of pile driving does not necessarily make this course unique as many of the single strike characteristic signatures behave similar to blasting.*

*We are not aware of amiable data or measurements on impacts of excavators, vibratory compaction, the operation of dozers and so forth on fish.*

B) Are there instances when using a long-duration mechanical excavation method in lieu of short-term blasting actually creates a greater impact?

*Yes. There are examples of such projects in Appendix C. In some instances the mobilization of large equipment in environmentally sensitive areas can create more of a disturbance than a drilling platform floating on a river. Mechanical excavation to remove rock may take up to five times longer and can impinge on time windows restricting construction activities.*

**Question 4**

A) What current types of vibration criteria are being used to manage waterway impacts?

*Current vibration criteria are only in the form of suggested guidelines only in Canada and Alaska given in Section 7.1*

B) What studies are specifically cited to establish these criteria and how robust are the data and findings?

*There were no reliable studies on which the Canadian criteria were based. The old Alaska criteria of 0.5 in/s, which is no longer in effect, was based on the U.S. Bureau of Mines recommendations for the protection of historic above-ground residential structures and lab tests by Smirnov in 1954. Such reliance is not scientifically valid. New Alaska criteria are 2.0 in/s where incubating eggs are present. This limit was selected as a value below that which has been shown to cause mortality. Discussed in Section 7.1.*

C) Are the criteria suitable for effectively managing common construction practices without undue effort or cost, or are they overly restrictive considering the basis for the criteria and sensitivity of the aquatic environment?

*The Canadian standards are most certainly overly restrictive. The Alaska standard which are the only US standard the authors are aware of have been changed to 2.0 in/s which may be feasible for most projects.*

D) Are the criteria empirically, analytically or experimentally derived?

*Criteria are experimentally derived based on experiments that attempt replicate blast pressure transients. They are chiefly based on impacts or shocks form dropping with time durations or phase changes in the histories.*

E) Are there different criteria applicable to eggs resting on the stream channel vs. grown fish?

*Yes. Ground vibrations in terms of PPV are in place for embryos while water overpressures are the criteria for fish in the water. Velocity of the water molecules should be considered but never been experimentally measured. Complete discussions are provided in sections 4.0 and 7.0.*

**Question 5**

A) Is there a criteria deployment model that allows for a percentage of exceedance, potentially resulting in acceptable limits of environmental impacts (e.g., specific fish takes)? B) How would such a deployment model be measured/enforced?

*Often criteria (in term of air overpressure or vibration limits) for land-based construction and blasting vibrations have such allowances. We are not aware of such allowances for underwater blasting. Insofar as takes, there have been project-specific allowances for juvenile and adult fish kills. We are not aware of any reported exceedances on published projects.*

B) How would this be enforced?

*Measurements would necessarily be conducted by an independent fish biologist or qualified consultant capable of covering the impact area after blasting as well as downstream for some time after each event. Such monitoring and kill counts may be impractical because lethal injuries may not lead to mortality for several hours or days after each blast. Fish counts can be obtained using many methods including visual observation, hydroacoustic surveys, sampling, underwater cameras, nets, etc.*

**Question 6**

A) Is the science exact enough to determine the threshold level where damage to an ~~animal~~ fish becomes permanent, or lethal?

*No; more research is necessary to determine species-specific tolerances.*

B) Is recoverable injury acceptable?

*This type of question is up to the discretion of the regulating agencies/biologists. Some injuries such as temporary hearing loss, light external hemorrhaging and abrasion may be easier to recover from in ideal conditions. There are some injury assessment models that address this (fish* *index of trauma (FIT), response weight index (RWI) and the fish response severity weight index (FRSWI).*

C) Do different organisms have different tolerance levels for blast vibrations/shock and is the least tolerant fish's threshold always the one to be met?

*Tolerance levels are determined for fish by species, life stage, size, and fitness. The physiological characteristics of fish that make certain species more sensitive to vibrations include the presence, absence, or type (physostomous or physoclistous) of swimbladder. Other characteristics could include body shape, whether or not the species utilizes electroreception (rare in freshwater species), or if it is a hearing specialist.*

*Meeting the lowest threshold of all species would be determined by the regulatory agency in charge of the species. NMFS, USFW, or local fish and wildlife agencies would determine thresholds and usually the most restrictive limit has to be followed.*

**Question 7**

What is a reasonable approach for addressing vibration concerns? For example, should we simply adhere to the current methods for determining blasting (or other source) setbacks to meet empirical criteria or should we go to the expense to derive site-specific attenuation models? Maybe both?

*Site-specific attenuation modeling is always ideal to establish baseline vibration for the first test blast. Mitigation efforts can easily be traced by continuing attenuations monitoring. For ground vibration this is inexpensive. For hydrophone measurements in water to determine attenuation for overpressure, multiple sensor locations must be defined at lateral distances and at two or more water depths. This may be expensive as detailed site characterization requires a large number of instruments (hydrophones) and multi-channel, high-speed data loggers.*

*It should be stressed that measurement systems widely differ and there is lack of agreement among scientists regarding hydrophone and recording instrument design and operation. There currently are no standards and consistency among different project specifications for compliance measurement equipment. Additionally, some project specifications require research-level hydrophones and costly data acquisition systems that must be built to order.*

*Measurement system resolution, sample rates, and other issues with measurement must be addressed in guidelines sponsored by professional organizations and other multi-stakeholder working groups.*

**Question 8**

A) What construction vibration factors affect the recorded seismic energy in or near a water body? For example, are both ground-borne and airborne seismic waves problematic?

*Only ground vibrations are a factor. Air-born seismic signals tend to be reflected off water bodies and do not transmit well into water. The factor that affect energy in water are certainly amplitude, duration and frequencies as previously indicated.*

B) Do factors such as ground type and distribution, source type and location, groundwater table location, moving vs. standing water, water depth and velocity, frozen ground or water body, weather conditions, blasting delay times, etc. impact the seismic energy at the water body?

*The factors include the source site (blast design charge weights and delay timing or operational characteristics of the construction equipment generating energy at the source) and the physical/material properties of the transmission medium (soil and rock or water conditions such as flow velocity and direction). Water-saturation and frozen ground increases density and transmission characteristics. All of these factors affect attenuation of noise signals in various directions.*

**Question 9**

Are there other sources of non-construction vibration, natural or manufactured, that also impact waterways or are considered to compromise background levels normal to the habitat? For example, are traffic-induced air/ground vibrations associated with bridges or adjacent roads/rail lines considered impacts to waterways? Are there vibration levels associated with turbulent flow (e.g., nearby rapids, flood stage water conditions) that might naturally exceed established construction standards?

*Natural background underwater disturbances can include noise from hydroelectric turbines, boat motors and river water flow velocities that may be well above pressure limits during spring run-off. Regularly occurring events that raise pressure levels are usually classified as background or ambient levels. Single disturbance events such as traffic accidents or landslides could create dramatic increases in pressure. However, these pressure-time histories would look very different from a blast.*

**Question 10**

A) What methods are available to quickly and easily measure construction vibration impacts in water bodies?

*Vibrations are easily and cheaply measured using geophones at the bottom of water. Low pressure range (less than 47 psi) hydrophones that are made to work with blasting-type seismographs (as opposed to very expensive research-based high-speed data recorders) are also very fast to deploy and inexpensive to utilize. Sample rates are limited to 65,000 S/s which is often sufficient for most vibrations if sound pressure reporting is required.*

B) Is it necessary to measure vibration energies within the water body, or can ground measurements at the edge of water be used?

*Vibration compliance in terms in velocity for substrata must be measured on solid land. We have found that setting a geophone adjacent to the water gives the same peak amplitude and frequencies as a geophone placed in the water at the bottom. However, more research in this area is needed. If overpressure measurements are required, hydrophones must be placed in the water. This is easily performed as long water-tight cables only need to be inserted into the water with a surface float and anchored in place.*

C) Are there any standards for how to collect data in support of the criteria limiting construction vibrations?

*For water overpressures, there are no measurement standards. The need for standards is paramount. For ground vibration and substrate vibration the standards are very clear and supported by the blasting and monitoring professional industries. There are currently no measurement guidelines or standards at this time for the use of hydrophones.*

D) Are there operational limitations to measuring in-stream vibrations that impact our ability to determine if construction activities are working within appropriate ranges?

*There are none. Existing equipment is capable to do so at this time.*

**Question 11**

Are there cost-effective mitigation measures to meet current water body vibration criteria (e.g., bubble curtains, scare methods, work windows, blast shaping, delay management, ground slotting/trenching)?

*This is addressed is section 6.0. Slotting or trenching does not work as seismic wave travel through the earth's body and transmit to the surface away from the sources. The trench needs to be 50 ft or more in depth to prevent transmission of body waves.*

**Question 12.**

A) What types of project risks should we consider?

*Beyond impacts to fish, blasting near historic structures and below-ground utilities; Blast design to mitigate these risk are well established as long as criteria are followed. The biggest "risk" is that of dealing with other federal and state agencies and the unforeseen concerns that may come to light once project planning commences. See Section 8.0.*

B) Schedule impacts?

*Schedule impacts can occur when federal and state agencies have different protection and performance standards or unforeseen issues come to light creating project delays and increased costs. The most recent example of this is the Columbia River Channel Improvement. Planning started 20 years prior to the start of the 4-month blasting project. Agencies were in litigation over habitat protection and improvement for 20 years. The project was completed without environmental degradation and no fish kills.*

*Other schedule impacts have occurred when communication breaks down with community members or special interest groups during the permitting stages.*

C) Mitigation measures costs?

*Mitigation measure costs must be considered by the contractor to meet performance specs. If reasonable limits are in place, mitigation is part of the rock removal costs to meet the limits.*

D ) Testing and monitoring costs?

*Monitoring costs are normally part of the earthwork contractor's costs. Project owners and general contractors are under the opinion they do not want to assume the risks associated with off-site damages and injury of blasting and rock removal. However 3rd party monitoring by a reputable subcontractor is extremely important.*

*Land-based and underwater blast monitoring costs are site- and project-specific. Large projects that last 3-6 months or more can costs $300,000-$500,000 for the monitoring program. Small projects can cost on the order of $50,000 - $80,000.*

*Vibration monitoring costs for land-blasting alone can cost $800-$1600 per blast day.*

E) Who are the governing bodies of construction vibration impacts?

*Ground vibrations and airblast – state DOTs, Cities and some Counties; Project –Specific criteria are imposed to various project for BLM, USBoR, Army Corps.*

*Blast overpressure – State departments of game and fish, National Marine Fisheries Service and the U.S. Fish and Wildlife Service may set some standards. Others are project-specific.*

F) Are standards set by states, owning agencies, federal regulatory bodies, or others?

*Yes.*

**Question 13**

What technology developments or existing technology deployment opportunities exist to help address this issue? Are there particular forums that we should take advantage of to communicate our approach(es) to managing this issue?

*Risk mitigation uses control methods to lower source energy, transmission medium energy, or to isolate the receptor. There are no "high-tech" solutions but established practices that work well. The challenge is to manage the contractors charged to implement these practices and be accountable for exceedances.*

# APPENDIX B – EXAMPLES OF STATE RESOURCE AGENCY PERMITS FOR BLASTING

## California

A CDFW Senior Fish Habitat Supervisor provided an example of an approved blasting project in Siskiyou County. Proposed mitigation measures weren't based on any blasting specific technical information, but rather on avoidance techniques (Kevin Gale, personal communication, April 19th, 2013). A summary of the project follows.

**Project**: *Whites Gulch Dam Removal*
**Description**: "OSHA certified blasters from the California Department of Fish and Game (DFG) will use explosives to demolish a diversion dam (upper dam) on Whites Gulch in a tributary to the North Fork Salmon River which will allow fish access to approximately 1.5 miles of stream. The dam is a 2 ft. thick, 41 ft. wide, and 7 ft. tall concrete structure. The site will be dewatered by constructing a cofferdam upstream of the site using native streambed material and Visqueen and routing the water around dam via an existing pipe. DFG biologists will remove fish and amphibians and release them to a safe section of stream. The dam would then be drilled, explosive charges set, blasted, and debris removed from channel. All work will take place using hand labor and small gas, electric, or pneumatic powered hand tools. No heavy equipment will be used. Currently there are two downstream barriers (culvert and diversion dam) which are scheduled to be removed after the upper dam is removed. These structures preclude the possibility that coho salmon may exist in the project area. The project is scheduled to be implemented in August, 2009."

**Resource protection measures:** A blasting plan was submitted including the description of drilling and blasting methods, materials, timeframe, and aquatic life rescue and removal. These details were provided in the plan:

- Fish and other aquatic life will be removed from an area approximately 100 feet upstream and 100 feet downstream of the dam.
- A screen and sandbag barrier will be used to isolate the downstream pool and a 100 foot stream reach above the dam.
- The pools will be partially dewatered. Seining and electrofishing will be used to remove fish from the blast area. Rescued fish will be moved to existing upstream and downstream pools several hundred feet from the dam.

**Additional Review:** The USDA Forest Service (USFS) Environmental Assessment (EA) concluded that impacts from the sound of the blasting would not affect the salmon because of the distance of 1-½ miles. The EA states that pools will fill in after the dam is removed and stream gradient is not likely to change. The USFS recommends leaving significant large wood or rock structures in the channel for habitat complexity. The EA states that, "the indirect effects of the project in terms of reducing pool habitat will be more than offset by leaving rocks and logs around which the stream will scour. Bedrock along the river-left bank at both dam sites should reduce the risk of bank erosion following demolition." A Decision Notice and Finding of No Significant Impact was issued for the project.

## Oregon

ODFW maintains a website at http://www.dfw.state.or.us/lands/inwater/ that provides guidance for in-water projects that may impact fish and fish habitat. The Land Use and Water Way Alterations Coordinator provided some examples of terms and conditions for permits to use explosives in Oregon waters (Joy Vaughan, personal communication, April 18th, 2013). All projects included the same 'General Conditions' including:

1. The applicant shall make all necessary notifications 48 hours prior to commencement of blasting activities
2. The permit holder shall obtain necessary permissions before entering lands owned by another
3. ODFW permit is issued in the interest of fish and wildlife protection and does not consider other liabilities or permits that the applicant is responsible for obtaining
4. Potential pollutants should be stored away from the project site to prevent materials from entering the stream in case of spillage
5. Minimize disturbance of stream banks and streamside vegetation. Reseed disturbed soil in fall or spring
6. ODFW reserves the authority to halt or modify the project in case of excessive damage to natural resources
7. The permittee may be required to compensate the state if damaged fish are observed
8. ODFW employees shall be allowed access to the project area at all reasonable times for the purpose of inspecting work performed under this permit
9. ODFW approval for in-water blasting does not authorize the incidental take of ESA listed fish, that issue must be addressed with the National Marine Fisheries Service through the U.S. Army Corps of Engineers permit review process
10. Permit violations are subject to administrative or legal action, permit may be revoked, permittee is responsible for activities of all contractors on site
11. The applicant is responsible for warning recreational users and nearby property owners of potential dangers of blasting, warnings may be in the form of signs, letters, or personal contact
12. All blasting wire, dynamite, boxes, etc. must be cleaned up
13. A copy of the permit must be at the work site during operations

The permit examples provide include 'Notification Requirements' the applicant must make including

1. Notify the district fishery or habitat biologist at least 48 hours before actual blasting so the Department has the opportunity to have an observer present or conduct a pre-blasting site inspection
2. Notify local law enforcement agencies before blasting activities
3. Notify all adjacent landowners, renters, and recreational users within the affected area of the planned in-water blasting schedule. The notice must be by:
    a. Registered letters to adjacent landowners with return receipt;

   b. Publication in the local newspaper;
   c. Postings in the vicinity of the project; and
   d. Auditory warnings before blasting.
4. Applicant must provide evidence to the Department of compliance with subsections 3(a)-(c) at least three days before blasting occurs

Each permit contains a description of 'Compensation for Injury to Fish and Wildlife' that states "The applicant must compensate the State of Oregon for any injury to fish, wildlife, or their habitat resulting from failure to comply with the conditions of the in-water blasting permit, or from failure to obtain and in-water blasting permit. Compensation for such injury or damage will be determined as provided for in ORS 4996.705 and 496.992, and OAR 635-001-0025 and 635-410-0030.

A Permit does not relieve the permittee from liability for the injury to persons, property, or fish and wildlife or their habitat resulting from acts conducted pursuant to the conditions of the permit."

'Special Conditions' for each project reviewed are listed below.

**Project:** *Cougar Dam Fish Trap Construction*
**Special Conditions:** Since the blasting activities will occur outside the wetted channel and behind a cofferdam, impacts to aquatic species will be minimized. Because of the cofferdam and high velocities in the river, the permit states that a bubble curtain would likely not reduce risk at the site any further. In addition, the following requirements are stated

- Blasting shall be completed between April 15 and May 14, 2009. Work outside this period requires a variance from ODFW
- Detonation delays shall be used to reduce the force of the shock wave
- Remove as much debris as possible from the waterway. Place waste materials and spoils above the high water line and not in wetland areas
- Work area will be isolated from the river and de-watered, this can be done with a cofferdam or similar structure. Fish shall be removed from the area by a contractor with the appropriate permits.

**Project:** *North Santiam River Explosives Use*
**Special Conditions:**

- Initial leveling or test blast shall occur between August 22 and September 15, 2011 and may occur prior to cofferdam construction and de-watering. The remainder of blasting shall occur between August 22 and October 31, 2011.
- Blasting shall occur outside wetted channel behind a cofferdam in a de-watered area. A contractor with the appropriate permits shall remove fish from the area.
- Use detonation delays
- Remove debris from waterway, place waste materials above high water and not in wetlands
- Use native material for any backfill

- Use controlled blasting methods to reduce impacts to fish and wildlife. Methods include drilling excess holes that are left empty, delayed blast timing, blasting mats, stemming, etc.
- Restore all areas disturbed by construction and blasting
- All provisions in permit application and blasting plan are incorporated into this permit

**Project:** *Rogue River Explosives Use near Savage Rapids Dam*
**Special Conditions:** Since the blasting activities will occur behind a cofferdam, impacts to aquatic species will be minimized. A bubble curtain would likely not reduce risk at the site any further. In addition, the following requirements are stated

- Minimize impacts to migrating spring Chinook by blasting between August 13-17th or August 6-17th if a two week window is required. Contact ODFW for variance.
- Use detonation delays
- Remove debris from waterway, place waste materials above high water and not in wetlands
- De-water work area and remove fish prior to work. Fish salvage must be done by a contractor with appropriate permits

**Washington**

- A WDFW Regulatory Services Coordinator was contacted and provided a list of provisions that biologists can choose from in addition to writing individual project-specific methods to mitigate impacts. It was noted that WDFW rarely receives requests for projects involving blasting in or near fish habitat (Pat Champman, personal communication April 9th, 2013). The list of provisions follows
  - Charges shall be no larger than necessary to accomplish the task and shall be set in a manner (timing, frequency, location) such that in-stream concussion is minimized. Timing shall include micro-second delays to minimize impacts to fish.
  - All blast material shall be removed and deposited in an approved upland disposal site so it will not re-enter the stream.
  - The permittee shall be financially responsible for any fish kill. Should a kill occur, all blasting activities shall immediately cease and the Area Habitat Biologist listed below immediately notified. A written report detailing the fish kill and subsequent actions shall be submitted to the Area Habitat Biologist as soon as possible following the kill, but no more than 15 days subsequent to the fish kill.
  - A diver shall be on site and available for potential damage assessment following blasting activities.
  - Blasting operations shall be conducted during periods of low or no stream flow.
  - Methods (blasting mats, sandbag berms, etc.) to contain and control possible slide debris resulting from blasting shall be in place prior to any blasting.
  - Prior to any blasting, the permittee shall capture and safely move food fish, game fish, and other fish life from an area 75 feet upstream and 75 feet downstream from the blast site. The permittee shall have fish capture and transportation equipment ready and on the job site. Captured fish shall be immediately and safely transferred to free-flowing

water away from the blast area. Once fish are removed, the area shall be blocked to prevent the re-entry of fish into the blast area. This may require the use of block nets or seines. The permittee may request the WDFW assist in capturing and safely moving fish from the job site to free-flowing water, and assistance may be granted if personnel are available.

- A bubble curtain shall be placed around the blast site to minimize impacts to fish.
- Approved fish scare tactics shall be used prior to blasting.

If at all possible, blasting shall occur in an area that is physically separated from the flowing stream, i.e., inside a cofferdam.

**Alaska**

The ADFG Division of Habitat maintains a website with information regarding Fish Habitat Permits and provides a link (www.adfg.alaska.gov/index.cfm?adfg=uselicense.explosives) to the Alaska Blasting Standard for the Proper Protection of Fish. Key points from the ADFG blasting standard are listed below.

***Project Review Period***

During the project review period biologists and applicants work together to avoid impacts to fish and embryos. Information is gathered such as species and lifestages of fish present, location of fish habitat, proximity to blasting, number of blasts, charge weights per delay, estimated maximum overpressures in water column and peak particle velocities in spawning gravels. Avoidance techniques suggested are using alternatives to blasting if possible, and blasting during times when fish or embryos aren't present

***Suggested Minimization techniques***

- scheduling blasting to avoid sensitive life stages,
- removing fish from the area and blocking them from the zone of impact,
- waiting until epiboly is complete if embryos are present in the gravel,
- scheduling blasting to avoid fish migrations,
- hazing fish from an area prior to blasting,2
- isolating or dewatering the work area,
- creating pressure wave interference,3
- using controlled blasting techniques following industry best management practices,
- surveying for debris and stream blocks after blasting and restoring fish passage,
- resloping, restoring, and revegetating disturbed streambanks, and
- removing all shock tube, explosive packaging, and wires from the worksite.

***Suggested Mitigation techniques***

Mitigation techniques include monitoring overpressures in the water column and vibrations in spawning gravels, and predicting pressures and vibrations that might cause injury. When monitoring is necessary, a list of requirements include the submission of monitoring reports with the following information.

- seismograph serial number, sensor type, and calibration date of all equipment,
- recording mode, trigger level, and sample rate,
- number of blasts,
- upstream and downstream sensor orientation with actual and scaled blast distances,
- date and time of shot,
- maximum charge weight per delay,
- overpressure time history plot with peak overpressure,
- peak particle velocity, frequency at peak particle velocity, and predominant frequency,
- fish mortality, and
- before and after photos

***Information Submission***

All monitoring reports are collected by the Department Director to be used to evaluate and revise the blasting standard as necessary.

# APPENDIX C – EXAMPLES OF PROJECT IN WHICH BLASTING IS THE BEST ALTERNATIVE

## USFS, Duffield and Fish Bay Fish Passage and Habitat Improvement Projects

Logging activities in the 1960's and 70's in the Tongass National Forest in Southeast Alaska left behind thousands of log stringer bridges and culverts. Today the dilapidated structures are collapsing into and damaging high value salmon habitat in remote areas. In order to restore fish passage blocked by failed structures and prevent further damage to fish habitat, in 2006 the USDA Forest Service Sitka Ranger District proposed to remove 67 log crossing structures obstructing fish access to approximately 19 miles of streams. Mechanical removal of the structures was considered and determined impracticable due to the remote location and overgrown condition of original dirt access roads. The monetary costs of rebuilding 9 miles of road and resource impacts from heavy equipment were much higher than removing the structures with explosives. Explosives and equipment were brought in by boat and helicopter and a remote camp was setup for USFS blasters and ADFG biologists to work from. In-water overpressures were monitored and an attenuation for log structure removal in shallow streams was developed. Fish were not removed work areas and were observed after blasting. In several instances fish were observed with normal behavior in the blast area immediately before and after blasting. On a few occasions salmon mortality was observed. Portions of the log structures were fragmented during the blast and heaved into the streams. The addition of large woody in an alder dominated forest created holding pools for spawning adults and out-migrating salmon smolts, and overwintering habitat for resident trout species and juvenile salmon. Due to the immense benefits to fish habitat and cost savings, the project was deemed a success by state and federal agencies despite the short-term impacts to fish.

## USFS, Fish Habitat Enhancement Projects

On several occasions the USDA Forest Service has requested and received approval from the State of Alaska Department of Fish and Game to use explosives to improve fish habitat. Explosives have been used on three known salmon streams (Indian River, Kizuchia Creek, and Kanalku Creek) to blast 'jump' pools into waterfalls allowing returning spawning adult salmon access to more upstream habitat. The blasted pools do not require maintenance, as would a man-made fish ladder, and allow fish natural access to more habitat saving costs and benefiting salmon habitat.

In 2013, explosives were used to blast jump pools into Kanalku Creek in a designated Wilderness Area on Admiralty Island in Southeast Alaska. Due to unusually high flow conditions during a work window designed to avoid impacts to fish, blasting took place near the peak migration time for adult sockeye salmon (*Oncorhynchus nerka*). ADFG biologist isolated the work area and removed as many fish as possible in the difficult terrain. A contractor measured in-water overpressures and vibrations, which were as low as 6.6 psi (45.5 kPa) and 0.73 in/s (18.5 mm/s) respectively. Eighteen injured or dead fish were recovered after the blast and several living fish were observed swimming in the area. The project was concluded successful, as the long-term benefits of increased salmon escapement should outweigh the short-term effects of the mortalities.

**US Army Corps, Columbia River Channel Improvements**

In 2009 blasting was conducted for the U.S. Army Corps of Engineers on the Columbia River near Saint Helens, Oregon. Blasting was part of the final phase of a dredging project and required a total of 99 blasts over four months to remove over 300,000 $yd^3$ of rock from the river bottom. The project underwent a lengthy environmental review and project conditions included an extensive and costly environmental monitoring plan to protect the 13 ESA listed species in the project area. The environmental review mandated a caged fish exposure study, marine mammal and bird observers, acoustic surveys, overpressure monitoring, and stipulated an allowable incidental take of no more than 10 adult and 50 juvenile ESA listed species. Upon project completion, there were no impacts to marine mammals, the cumulative take juvenile and adult salmon was zero, and three dead sturgeon were recovered in the blast area. The project was completed ahead of schedule and complied with all environmental stipulations despite extremely harsh working conditions that included freezing weather, river debris, high current and flows all in an active shipping channel. A well-executed test-blasting and overpressure monitoring program and an adaptive management strategy contributed to the success of this project.