Underwater Blast Pressure Monitoring for the Columbia River Channel Improvement Project

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Abstract

Blasting was conducted for the Army Corps of Engineers (Corps) in the Columbia River near Saint Helens, Oregon during 2009 and 2010 to deepen the navigation channel as a final phase of a dredging project to accommodate larger container ships. The Columbia River Channel Improvement Project (CRCI) required 4 months to blast and dredge 300,000 yd^3 (229,366 m^3) of basalt from the bottom of the channel to allow Post-Panamax vessels with drafts up to 50 ft (15.2 m) access to the Ports along the River. Explosives charges were limited to 90 lbs (40.8 kg) per delay for the protection of fish and marine life in the area. A fish mortality study and marine mammal monitoring program was also required by the Corps. Underwater overpressure monitoring was required for each blast and peak overpressures measured 10 ft (3.1 m) above the river bottom 140 ft (42.7 m) from the closest blast hole were not to exceed 70 psi (483 kPa) with a cautionary level of 40 psi (276 kPa). Specifications required sampling rates of 500k S/s and PCB Peizotronics tourmaline pressure sensors. The Corps granted permission to co-locate additional ceramic-type sensors at different sampling rates to design redundant monitoring systems 140 and 300 ft (42.7 and 91.4 m) from blasting and develop a site-specific overpressure attenuation model for the project. This paper presents the correlations of overpressure with cube-root scaled distance factors, a comparison of measurements using three different pressure sensor systems, and a discussion of blast design influence on overpressure measurements.

Background

The Columbia River Channel Improvement (CRCI) Project was designed to improve the deep-draft transport of goods on the authorized navigation channel, to provide ecosystem restoration for fish and wildlife habitats, and minimize impacts of blasting, dredging, and disposal of degraded materials on threatened and endangered fish species and their habitat.

The Project proposed to deepen the navigation channel enabling the use of larger, more efficient vessels to transport commodities. This required 300,000 yd^3 (229,366 m^3) of basalt rock to be blasted and dredged near St. Helens, Oregon along a mile-long (1,609 m) region shown in Figure 1. Blasting and removal was estimated to cost $25 million due to extensive safety and environmental precautions required to accommodate commercial, fishing, and recreational traffic, and protect endangered species.

The Columbia River Channel Improvements project underwent extensive environmental review beginning in the 1990's and in 2002 the National Marine Fisheries Service (NMFS) issued a Biological Opinion (BO) finding that the project was unlikely to adversely impact any of the 13 Endangered Species Act of 1973 (ESA) listed species (including Chinook, chum, and sockeye salmon, steelhead

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[1] Employed by Contract Drilling and Blasting LLC and Aimone-Martin Associates, LLC during project

trout, and Stellar sea lions) in the project area. The BO mandated research, monitoring, adaptive project management, and stipulated an allowable incidental take of fish that die as a result of blasting to no more than 10 adult and 50 juvenile ESA-listed salmonids. In accordance with the terms of the BO, the Corps contracted with Pacific Northwest National Laboratory (PNNL) to implement an extensive environmental compliance monitoring program during blasting. The monitoring plan included a marine mammal and protected bird watch program, a sturgeon monitoring program, survey and estimation of take for ESA-listed fish, and a caged juvenile salmonid study.

In 2009 J.E. McAmis was awarded a 3M yd^3 (2.3 M m^3) dredging contract near St. Helens, Oregon. The work window for rock blasting was restricted from November 1 to February 28, 2010 to minimize incidental take of ESA-listed fish. Controlled rock drilling and blasting was performed by Contract Drilling and Blasting LLC (CDB) and in-water and land-based monitoring, public relations, project web-site development and pre-blast surveys were performed by Aimone-Martin Associates, LLC (AMA).

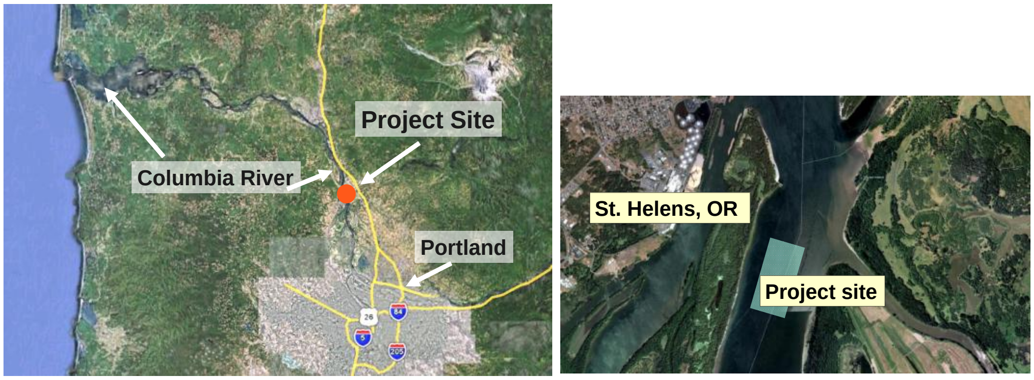


Figure 1 Location of blast blasting project site

Rock Blasting

A total of 99 blasts including six test blasts were conducted and completed ahead of schedule by February 5, 2010. Drilling and blasting operations were conducted from a barge positioned in the navigation channel. Drilling took place 24 hours a day and blasting normally occurred twice a day close to sunrise and sunset six days per week. Bore hole diameters were 4.5 in (114 mm) drilled to an average depth of 11 ft (3.4 m) and stemmed a minimum of 30 inches (0.8 m) with ½ inch-minus (19 mm) crushed rock. Bulk emulsion and 2-lb (0.9 kg) cast boosters were loaded. Surface delay nonelectric detonators with 25 ms and multiples of 42 ms were used. Four foot (1.2 m) up to 12 ft (3.7 m) square blast hole patterns were drilled in one (single row) to seven rows. Multi-row patterns were detonated on a center “V” or corner echelon sequence.

Blast-Induced Overpressure Measurements

Two hours prior to a scheduled blast the pressure monitoring vessel was dispatched to position and deploy sensors, test background current “noise” in the measurement system and await the blast. Blast-induced overpressures were measured and reported immediately after each blast to show compliance so that drilling for the next shot could begin as soon as possible. A site-specific attenuation model to predict water overpressure as a function of cube-root scaled distance (CRSD) was developed and actively updated. Final overpressure monitoring reports and predictions were submitted within the hour.

The project provided the opportunity to test and compare different pressure measurement systems and sample rates. Pressure measurements were also compared and correlated with various blast design parameters. However, such correlations were difficult due to variable drilling and loading conditions. Blasts in fractured basalt with voids and clay seams often resulted in variable overpressure measurements based on the relative degree of charge confinement producing unusually low time-histories or isolated high pressure spikes. Careful drill logs were kept during the project and were utilized to help explain variability and separate the influences of charge confinement.

Instrumentation Systems and Specifications

Project specifications required compliance pressure measurements with a single PCB Piezotronics type 138A01 fluid-encased tourmaline sensing element with a frequency range of 2.5 to 200 KHz and working pressure range up to 1,000 psi (6,895 kPa). The sensor package was terminated with a 3 ft (0.9 m) pig-tail of 10-32 coaxial cable that had to be soldered to an RG58 coaxial cable to render a strong, water-proof connection that could withstand the Columbia River's harsh currents, tidal fluctuations, and floating debris. The integrated circuit sensor was powered by a 482C05, 4-channel signal conditioner and data recorded using an 8-channel HBM Genesis 7t (GEN7t) high-speed data acquisition system and measurement rate of 500,000 samples/sec (500 KS/s). Digital data was provided to the Corps in ASCII format or Nicolet (.wft) format.

The compliance sensor was required at a distance of 140 ft (42.7 m) from each blast location suspended 10 feet (3.1 m) above the river bottom. Peak water overpressures were limited to 70 psi (483 kPa) with a cautionary limit of 40 psi (276 kPa). Specifications required that the PCB sensors be factory calibrated every 10 blasts or when questionable data was recorded. Since the PCB sensors could not be field-calibrated, a large number of replacement sensors were kept on hand. Cutting sensors from cable leads required constant re-soldering and water-proofing on a regular basis which was challenging to accomplish, extremely time consuming and very costly to the project.

Due to the critical nature of the measurements, harsh monitoring environment, and specific monitoring requirements, redundant systems and additional sensors were requested and ultimately approved by the Corps. The redundant system at the compliance location included a B&K 8105 ceramic sensor with reinforced underwater coaxial cable and field-calibration capabilities. The 8105 maximum working pressure was 1,500 psi (10,342 kPa) with a frequency range from 0.1 Hz to 180 kHz and was measured using the GEN7t system. A third stand-alone system consisting of an Instantel ceramic hydrophone and Series III Minimate with a maximum pressure and frequency range of 47 psi (324 kPa) 8 to 500 Hz range, respectively, was also deployed at the compliance location in the event of a GEN7t failure. After several comparisons and tests between the PCB and B&K sensors, the requirement for factory calibration of PCB sensors every 10 blasts was eliminated.

Measurements from a second location were crucial for the development of a reliable attenuation model. Therefore, all three sensor types were deployed both at 140 and 300 ft (42.7 and 91 m) from the blasts. The final instrumentation schematic of the tourmaline (PCB) and ceramic (B&K and Instantel) measurement systems is provided in Figure 2.

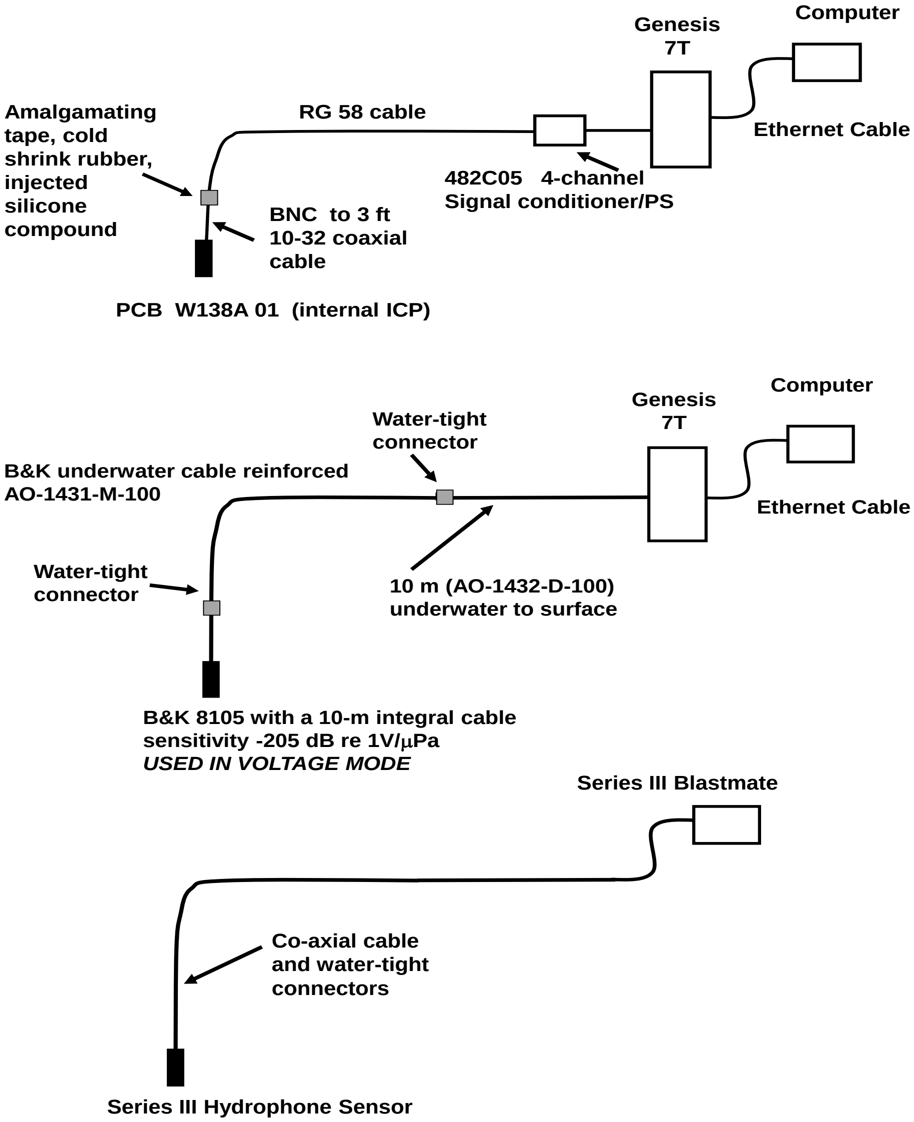


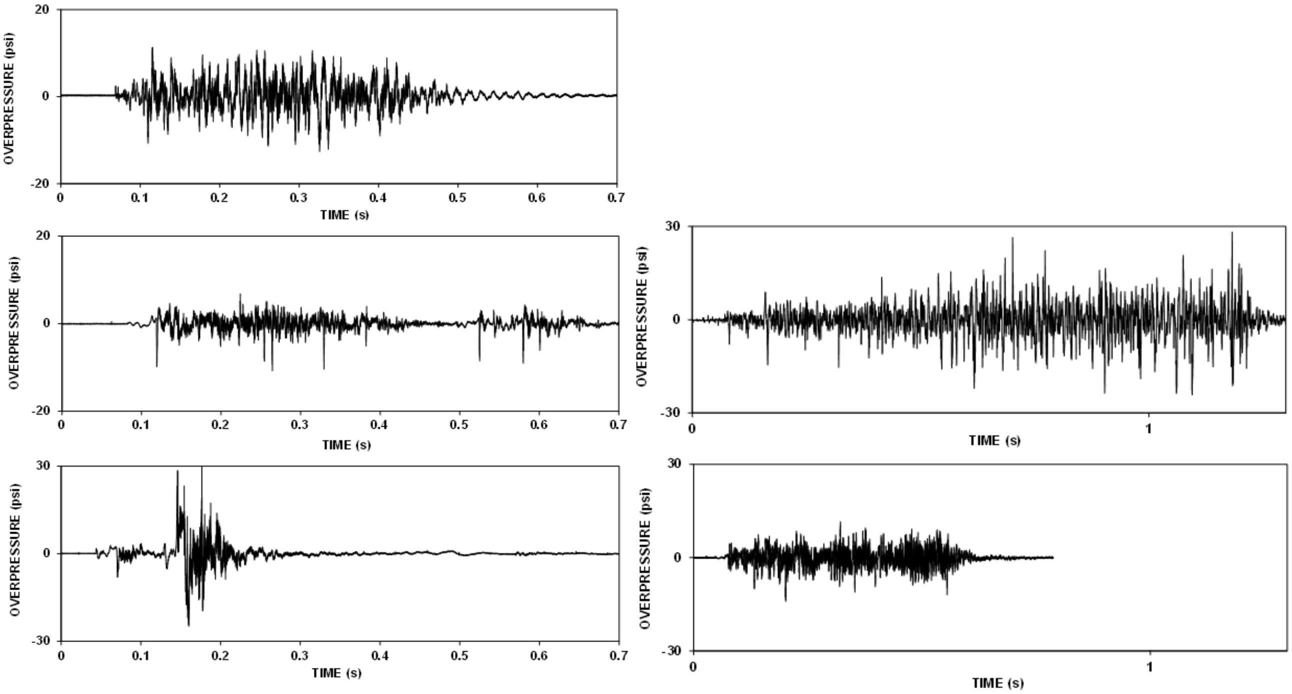
Figure 2 Schematics of PCB and B&K pressure measurements systems

Results

The CRCI project provided the opportunity to measure and analyze a large number of underwater blasts and develop an attenuation model that may be applied to other similar blasting projects in a deep river similar to the Columbia. The river bottom conditions and rock quality for drilling and explosive loading purposes were highly irregular and contributed to varying degrees of charge confinement that affected overpressure amplitudes. When loading within fractured rock with clay seams, explosive energy dissipated within the weak rock and overpressures were often lower than expected. Occasionally, the blast area included sloping faces or high spots with reduced lateral confinement that created isolated spikes or higher than expected pressure time-histories. To identify blasts that might be classified with well- or poorly-confined explosive charges, careful notes were taken during drilling to identify competent or highly fractured rock. The use of multi-beam bathymetry was useful to identify river bottom elevation contours and the exposed rock surface areas to be blasted.

Pressure Measurements

Figure 3 provides examples of characteristic pressure time-histories for competent rock and well-confined charges (top figures) and for blasts within highly fractured rock containing voids and/or clay seams.



(a) (b)

Figure 3 Pressure time histories (a) for a well-confined 3-row 33-hole blast (-12.7 psi peak) (top), a 3-row, 4-hole blast in highly fractured rock (-10.8 psi peak) (middle) and a single line of 3 holes in broken rock with voids (30.6 psi peak) (bottom), and (b) for a well-confined 7-row 62-hole blast, blast duration 1503 ms (29.2 psi peak), (top), a 5-row, 65-hole blast in fractured rock, blast duration 503 ms (-14 psi peak) (bottom)

In less competent rock or small shots with less confinement, pressure time-histories were non-uniform with sporadic spikes. In many cases, pressures were low (as in Figure 3, right, bottom). Pressure measurements at nominal deployment distances from the blasts of 140 and 300 ft (42.7 and 91.4 m) were separated into well- and poorly-confined categories based on rock quality determined during drilling for comparison, giving the following data statistics:

	140 ft (42.7 m) nominal distance		300 ft (91.4 m) nominal distance	
Data Statistic	well-confined	poorly-confined	well-confined	poorly-confined
Number of data	128	107	96	70
Maximum (psi)	57.8	83.5	29.2	82.2
Minimum (psi)	12.9	4.4	6.2	3.5
Mean (psi)	23.5	18.8	13.0	14.3
Median (psi)	23.0	14.8	13.0	10.2
Standard deviation	±7.0	±12.9	±4.4	±13.3

Figure 4 provides histograms for the four data sets separated by measurement distance and degree of confinement to illustrate the uniform distribution of well-confined blast overpressures. The mean and median are identical indicating a symmetric distribution of data. The poorly-confined data sets show a large number of low pressures (e. g., data skewed to the right) and a few high spikes.

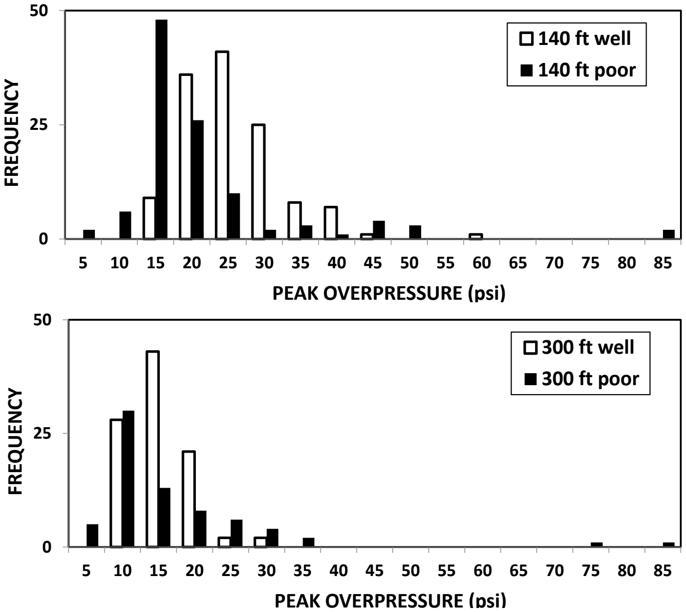


Figure 4 Distribution of pressure measurements at nominal deployment distances of the blast of 140 ft (top) and 300 ft (bottom) (42.7 m and 91.5 m) for well-confined and poorly-confined blasts

Peak Frequency Measurements

The distribution of peak frequencies throughout time-histories was highly random and could not be correlated with design parameters at this time. Histograms of peak frequency values for the highest non-time correlated positive and negative peaks, regardless of confinement or rock quality, in each time history are given in Figure 5. Summary statistics are given as follows:

	140 ft (42.7 m) nominal distance		300 ft (91.4 m) nominal distance	
Data Statistic	positive peaks	negative peaks	positive peaks	negative peaks
Maximum (Hz)	6,928	7,547	6,953	2,500
Minimum (Hz)	54	54	22	53
Mean (Hz)	388	306	297	335
Median (Hz)	192	175	184	186
Standard deviation	±771	±688	±588	±464

Peak frequencies generally fell below 7,600 Hz and averaged 347 and 316 Hz at nominal distances of 140 and 300 ft (42.7 and 91.4 m), respectively. When frequencies were separated into positive and negative values, the close-in peak frequencies (140 ft, 42.7 m) averaged 388 Hz while the negative peaks averaged 306 Hz. These frequencies did not significantly decay at 300 ft (91.4 m).

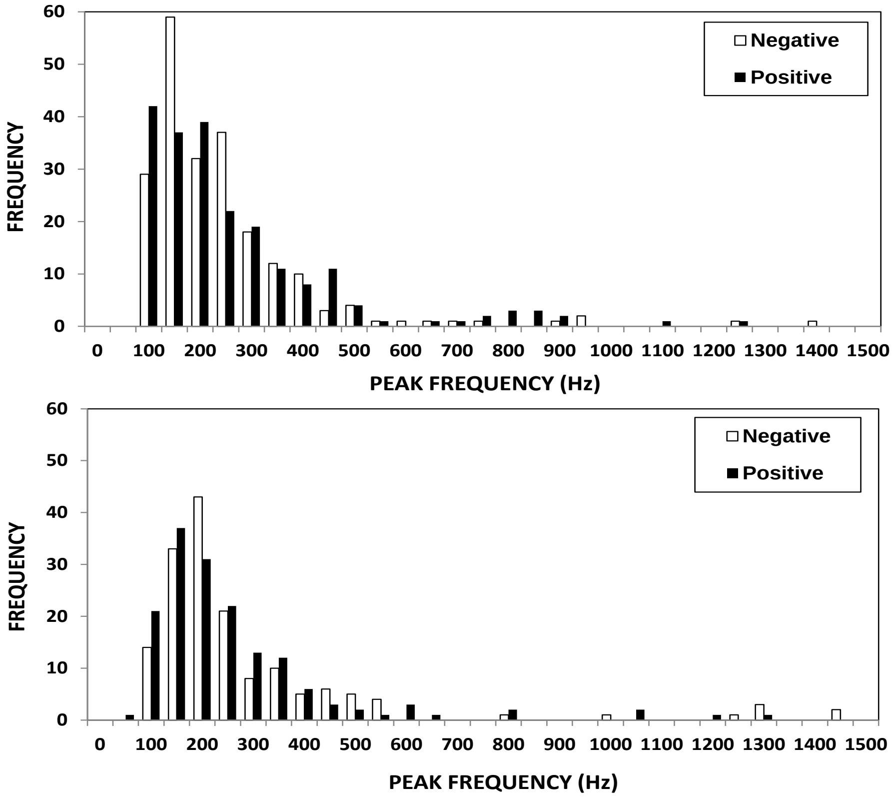


Figure 5 Distribution of peak frequencies at normal deployment distances of the blast of 140 ft (top) and 300 ft (bottom) for positive and negative peaks within each time history

Attenuation of Overpressure

Attenuation plots given in Figure 6 show pressure decay with scaled distance for well- and poorly-confined charges (left) and for only well-confined charges in competent rock (right).

The linear regression best-fit attenuation model for well-confined charges for the project is given as

$$\text{Overpressure, P (psi)} = 928\ \text{CRSD}^{-1.04} \qquad \text{(Imperial)}$$
$$\text{Overpressure, P (kPa)} = 420\ \text{CRSD}^{-1.04} \qquad \text{(metric)}$$

Where CRSD is cube-root scaled distance ($\text{ft/lb}^{1/3}$, $\text{m/kg}^{1/3}$) and $R^2 = 63\%$. The data scatter is attributed to the differences among the three types of sensors and different sample rates, position of each sensor in the water, currents at the time of recording, and background noise from operating dredging equipment. The attenuation model along with the upper bound line can be used to predict overpressures based on maximum charge weight per delay and distance in similar conditions for full-scaled blasts in deep water.

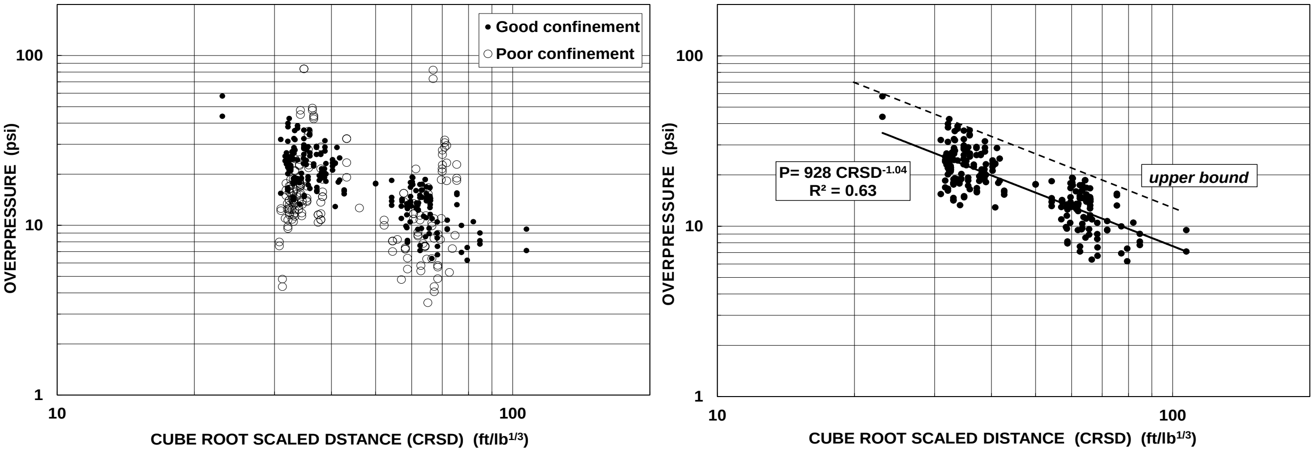


Figure 6 Overpressure versus cube root scaled distance for well- and poorly-confined charges (left) and for well-confined charges only (right)

Comparison of Sensors and Sample Rate

Figure 7 shows scatter plots comparing peak pressures measured using sensor pairs at two distance ranges from blast holes. B&K ceramic and PCB tourmaline sensors were recorded with a sample rate of 500k S/s (left plot). On average, B&K sensors recorded 95% and 87% of the peaks recorded with the PCB sensor at nominal distances of 140 and 300 ft (42.7 and 91.4 m) from the blasts, respectively. A comparison of the Instantel system pressures recorded at a nominal 65k S/s with PCB recorded pressure using 500k S/s (right plot) indicates the data are scattered uniformly about a slope of unity at distances less than 200 ft (61 m). At farther distances, pressures measured with the ceramic sensor generated, on average, 84% of the pressure amplitudes with the higher sample rate. A one-way analysis of variance (ANOVA) was calculated to compare the means of all three sensor types. The results did not support a difference in mean pressures between sensor types (F [2, 403] = 1.832, p = 0.161). Additionally, recorded pressures were regressed against CRSD values and compared by sensor type. When the effects of CRSD were removed, the type of sensor did not significantly affect pressure measurements ($p > 0.05$, SE = 0.11).

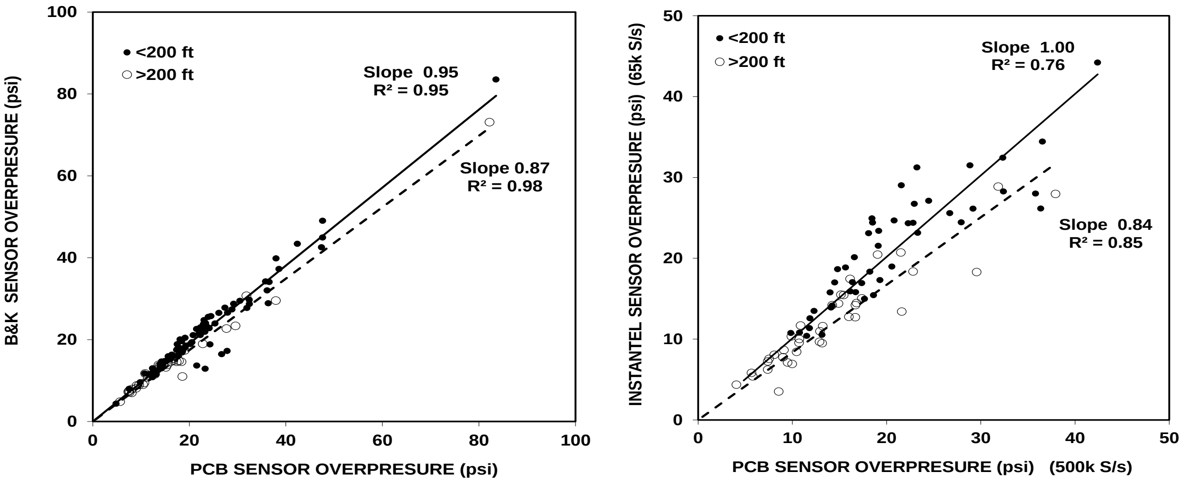


Figure 7 Overpressure scatter plots for co-located pressure sensors (left) B&K and PCB at similar sample rates and (right) Instantel ceramic and PCB at two different sample rates

Blast Design Influence on Overpressure

Parameters used to evaluate the influence of blast design on measured pressures were limited to shot surface area, as it affected pulsing the water-rock interface, and down-row delay timing. No correlations were noted between overpressure and powder factor, number of holes, or number of rows at this time. The correlation between pressures measured at a nominal 140 ft (42.7 m) and shot surface area is shown in Figure 8 for three drill hole patterns including rectangular center pull "V" and echelon patterns and a single row of holes.

Single rows clearly generated the lowest overpressures while "V" and echelon patterns provided the same distribution of overpressure correlated with blast surface area. The correlation between surface area and overpressure is similar to that observed for sound pressure level for surface blasts.

The influence of delay timing used down the rows was evaluated in Figure 9 by combining peak values for overpressure and frequency plotted against peak frequency. This plot can be thought of as representing the rate of overpressure deposited into the water as a function of excitation frequency. Data were separated for down row timing of 25 ms and 84 ms delays and incorporated both highest positive and negative spikes for all time histories, irrespective of rock quality and charge coupling. The distribution of high "spikes" from possible unconfined charges based on delay timing can be readily observed. Figure 9 reveals that high overpressure spikes and associated high frequencies occurred for 25 measurements when using 84 ms timing along the rows. Such "spikes" were not observed for any blasts when using 25 ms down rows. It appears that the longer delay time provided more time for rock movement between delays, creating smaller effective burdens for subsequent charge detonations and a higher probability for less-than-ideal confinement. Shooting holes 25 ms apart provided better overall confinement. This observation has important implications for underwater blasting and the protection of fish. As such, delay timing and rock quality correlations with measured overpressure amplitudes and frequencies should be studied further.

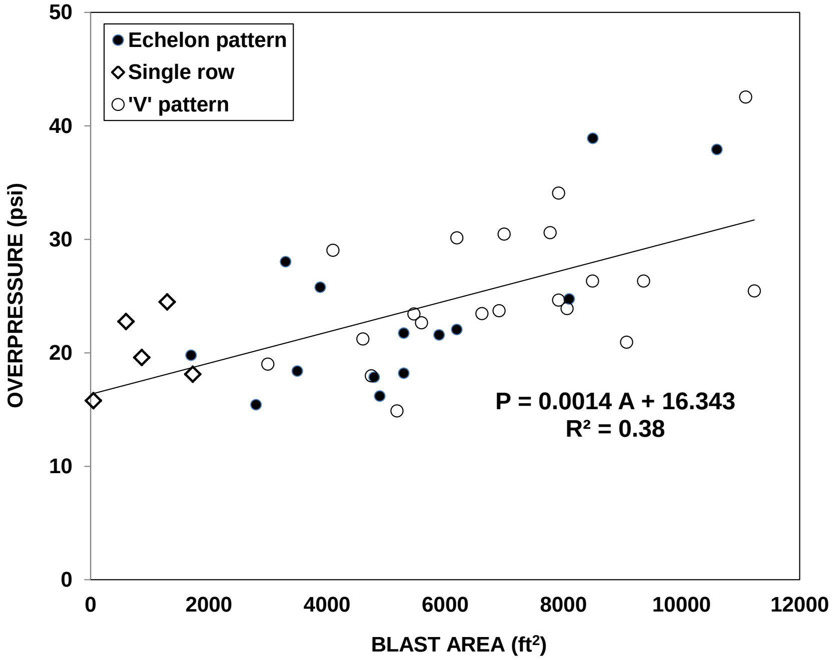


Figure 8 Overpressure versus shot surface area for three initiation patterns

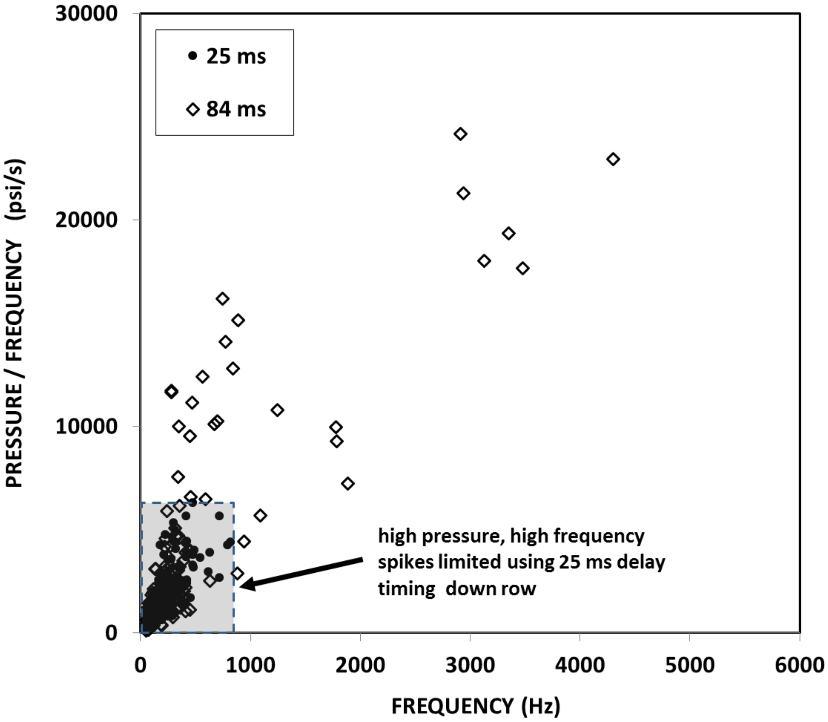


Figure 9 Ratio of peak overpressure and peak frequency versus frequency used to illustrate the effects of row timing on the probability of high pressure spikes to occur

Environmental Monitoring

Methods and results of the environmental compliance monitoring program performed by PNNL are detailed in a compliance monitoring Completion Report (Carlson et al. 2011). In summary, harbor seals and California sea lions were observed and not impacted during the project. Three dead sturgeon were recovered after blasting and no dead salmonids were observed. The cumulative take of juvenile and adult salmon was estimated to be zero since blasting operations were completed before the annual peak of juvenile salmon emigration.

During the caged fish study, juvenile Chinook salmon and rainbow trout were caged and placed 108 to 416 ft (33 to 127 m) from blasting. A total of 1,118 fish were dissected and examined after exposure and blast-related injuries were categorized and rated for severity. Researchers found that maximum positive pressures (negative peak pressures not included) from blasting were positively correlated with fish injury categories and severities and provided a model to describe the relationship. The Completion Report concluded that the fish injury model should be used to assess blast effects on depth-acclimated juvenile salmonids from buried explosive charges.

Conclusions and Recommendations

The information in this report represents an initial exploration of blast-induced underwater pressure measurements for a specific river. Overpressure measurements similar to those presented in this report should be collected and analyzed for rock blasting effects on marine species in and near rivers with variable speed currents and depths, lakes, reservoirs, and salt-water environments. More attenuation measurements are needed and overpressure correlations with blast design parameters should be performed to advance the field of knowledge in aquatic species protection.

References

Carlson T.J., G.E. Johnson, C.M. Woodley, J.R. 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.