UNDERWATER ACOUSTIC MEASUREMENTS OF VIBRATORY PILE DRIVING AT THE PIPELINE 5 CROSSING IN THE SNOHOMISH RIVER, EVERETT, WASHINGTON

Emergency Water Transmission Pipeline Repairs Construction Project
City of Everett Project No. UP 3148
URS Project No. 33756899

Prepared for:

URS Corporation
1501 4th Avenue, Suite 1400
Seattle, WA 98101-1616

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GREENERIDGE SCIENCES, INC.

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CONTENTS

FOREWORD

During the first half of November 2004, the City of Everett completed the Emergency Water Transmission Pipeline Repairs Construction Project No. UP 3148, that consisted of stabilizing the underwater sections of Pipeline 5 at the Snohomish River and Ebey Slough crossings. The repairs included the vibratory driving of several 14-inch steel H-piles near the pipeline, and securing the pipeline to the piles. The City contracted with Advanced American Diving (AAD) Service Inc. of Oregon City, Oregon, to complete the construction, and URS Corporation of Seattle, to complete the design and construction inspection.

The key goals of the project were to determine the level of effect (if any) of protected salmonids and to communicate the findings to the Federal agencies. To achieve these goals, a Best Management Practice (BMP) approach to the work was developed, and URS retained Greeneridge Sciences Inc. of Goleta, California, to monitor the underwater sounds produced by the vibratory pile driving and to characterize any potential impacts of the work on salmonids. To measure the potential impacts, Greeneridge completed underwater acoustic measurements on November 11 for various depths and ranges during some of the deeper pile-driving operations in the Snohomish River. The measurements were made by William Burgess and Susanna Blackwell of Greeneridge under the direction of Andrea Balla-Holden of URS.

This report by Greeneridge describes the underwater acoustic monitoring work that was completed, presents the measurements that were taken, discusses the analyses of these measurements, and provides conclusions that assess the level of effect during the construction.

by URS Corporation
Seattle, Washington
20 January 2005

PREFACE

William C. Burgess (Senior Research Engineer, Greeneridge Sciences) prepared this report. Susanna B. Blackwell (Senior Scientist, Greeneridge Sciences) authored Section 5, "Potential Biological Effects," with contributions and review by Robert Abbott (President and Senior Fisheries Scientist, Strategic Environmental Consulting).

Charles R. Greene, Jr. (President and Principal Scientist, Greeneridge Sciences) supervised this effort and suggested many improvements to this report. Andrea Balla-Holden (Senior Fisheries Biologist, URS Corporation) managed the measurement program and assisted with data acquisition. Richard Clark (Resident Construction Inspector, URS Corporation) coordinated the measurement program with construction activities. Mike Johns (Project Superintendent, Advanced American Diving Service) captained the monitoring vessel and provided details on the operation of the vibratory driver. Jenifer Galatas (Project Manager and Construction Manager, City of Everett) managed the construction project on behalf of the City of Everett, while Paul Crane (Environmental Planner, City of Everett) took the lead on environmental permitting as well as local, state and federal interagency communications and coordination. The City of Everett, Washington, supported this work.

1 SUMMARY

In November 2004, Advanced American Diving (AAD) Services Inc., under contract to the City of Everett, Washington, completed repairs to a water-transmission pipeline where it crossed the bottom of the Snohomish River near the City. The repairs included inserting steel H-piles about 60 ft into the riverbed using a vibratory pile driver. As part of its commitment to Best Management Practices (BMP) the City requested monitoring of the underwater sounds produced during the vibratory pile driving and an assessment of the potential impact of those sounds on protected fish species, including threatened bull trout and Chinook salmon. A series of underwater acoustic measurements took place on 11 November 2004 at a variety of depths and distances from the piles being driven.

The measurements showed that the vibratory driver radiated an infrasonic tone, typically between 12 and 18 Hz, into the river and riverbed. The tone was responsible for received sound pressure levels up to 161 dB re 1 µPa at a range of 46 ft (14 m) and a depth of 15 ft (4.5 m), 3 ft (1 m) above the riverbed at that location. This maximum received level occurred when the vibratory driver was turned off and passed briefly through what appeared to be a resonant frequency at about 6 Hz before shutting down. More typical levels received at 46-ft (14-m) range fluctuated between 145 and 155 dB. The maximum sustained received level measured for the infrasonic tone was 156 dB averaged over a 79-s period.

Acoustic measurements at greater distances showed that the infrasonic tone attenuated rapidly with range from the vibratory driver as measured in the water column. At 627-ft (191-m) range the tone was no longer a significant contributor to broadband sound pressure level at hydrophones suspended in the water. Autonomous acoustic recorders placed on the riverbed, however, detected the infrasonic tone at levels over 10 dB above background out to a range of 1050 ft (320 m). These measurements are consistent with propagation of the infrasonic tone primarily in the sub-bottom with a boundary acoustic wave in the water diminishing rapidly with distance above the riverbed. This situation would be expected given that the river's shallow depths of 10–26 ft (3–8 m) would prevent normal propagation of infrasonic frequencies within the water column.

Comparison of these received levels with those discussed in the available literature indicated that salmonids located in the Snohomish River adjacent to the site may have heard the vibratory-driver sounds under these conditions. The measured levels fell far short, however, of those discussed in the literature as resulting in physiological stress. The likelihood of a short-term avoidance reaction, potentially leading to increased stress or predation, remained unknown. Nevertheless, while short-term avoidance to the vibratory driver may have occurred, any such avoidance was likely to have had no greater potential impact than the avoidance behavior commonly carried out by Snohomish salmonids in response to other natural and anthropogenic stimuli in their habitat.

2 INTRODUCTION

On 11 November 2004, URS Corporation and Greeneridge Sciences, Inc., measured underwater sounds produced by vibratory pile driving at the Snohomish River crossing of Pipeline 5, a water-transmission pipeline for the City of Everett, Washington. The measurements took place in the river at ranges from 46 to 1116 ft (14 to 340 m) from the piles and at depths from 3 to 18 ft (1 to 5.4 m). Measurements were also made of ambient sound levels away from the driving site at a time when no pile driving was taking place. Using these measurements, an assessment was made of the sound field produced by the vibratory driver and the potential effects of that sound field on salmonids.

2.1 REVIEW OF UNDERWATER ACOUSTIC CONCEPTS AND TERMINOLOGY

The conclusions of this effort have been written to be accessible to a broad audience. The following brief tutorial on acoustics is provided as background for those readers wishing a deeper understanding of the data presented.

An ***acoustic wave*** is a disturbance in a field of physical particles, such as tiny volumes of air or water, that causes those particles to oscillate. As the disturbed particles move against undisturbed particles, the compression results in a localized increase in pressure. That pressure causes adjacent, formerly undisturbed particles to move away, spreading the disturbance outward from its origin. These alternating fluctuations of ***pressure*** and ***particle motion*** comprise the acoustic wave. Particle motion is described in terms of particle velocity or particle acceleration, whose metric units are meters per second (m/s) or meters per second squared (m/s^2) respectively. The metric unit for pressure is the pascal (Pa), approximately equivalent to 0.000145 pounds per square inch.

In acoustics, the word ***level*** denotes a sound measurement in ***decibels***. A decibel (dB) expresses the logarithmic strength of a signal relative to a reference. Specifically, the decibel is defined as

$$\text{decibels} = 10 \times \log_{10} \frac{(\text{signal amplitude})^2}{(\text{reference amplitude})^2}$$

Because the decibel is a logarithmic measure, each increase of 20 dB reflects a ten-times increase in signal amplitude (whether expressed in terms of pressure or particle motion): 20 dB means ten times the amplitude, 40 dB means one hundred times the amplitude, 60 dB means one thousand times the amplitude, and so on. Because the decibel is a relative measure, any value expressed in decibels is meaningless without an accompanying reference. In describing underwater sound pressure, the reference amplitude is usually 1 micropascal (µPa, or 10^{-6} pascals), and is expressed as “dB re 1 µPa.” For in-air sound pressure, the reference amplitude is usually 20 µPa.

A one-decibel change in sound level is considered to be (to a first approximation) the smallest change in sound level perceptible to a human listener. Often it takes a change of two or even three decibels to be perceptible, depending on the sensitivity of the listener. A change of +10 dB or -10 dB is perceived by a human listener to be, respectively, about a doubling or a halving of loudness. For example, a human would perceive a level of 90 dB to be twice as loud as a level of 80 dB. Note that this perception does not vary one-to-one with the pressure amplitude; despite sounding twice as loud to a human, a 10 dB increase in sound level reflects tripling of the sound pressure.

The level of a propagating sound depends on where it is measured. Adjacent to the source, sound levels vary in complex ways with the spatial distribution of the source, its proximity to the surface or bottom, and the presence of interfering objects such as a vessel hull. The ***source level*** of a sound is defined as the sound level that would exist at a distance of one meter from an idealized point source emitting the same sound as the actual source in question. However, most actual sources are not point sources. Therefore, one cannot typically measure source level directly by placing a hydrophone one meter from the source. Source levels are usually inferred from measurements made at greater distances or from computer models. Source levels carry units of dB re 1 µPa-m, although they are sometimes expressed in dB re 1 µPa at 1 m. Another measure of source strength is the bar-meter, where a bar equals 10^{11} µPa, or approximately one atmosphere.

As sound propagates away from its source, several factors act to change its amplitude. These factors include the spreading of the sound over a wider area (***spreading loss***), losses to friction between water or sediment particles that vibrate with the passing sound wave (***absorption***), ***scattering*** and ***reflections*** from boundaries and objects in the sound's path, and constructive and destructive ***interference*** with one or more reflections of the sound off the surface or seafloor. The sound level that one would actually measure at any given distance from the source includes all these effects, and is called the ***received level***. Received levels differ in dimensions from source levels, and the two cannot be directly compared. Received levels of underwater sound are usually presented in dB re 1 µPa, whereas the idealized source level at a distance of 1 m from the source is presented in dB re 1 µPa-m. The sum of all propagation and loss effects on a signal is called the ***transmission loss***.

In calculating an average sound level over a specified length of time, common practice is to square the sound pressures measured over that time and average them, obtaining a mean square pressure, and then compute 10·log(mean square) to obtain the ***sound pressure level (SPL)***. A mathematically equivalent procedure is to compute the square root of the mean square to obtain the ***root-mean-square*** or ***rms*** sound pressure, then compute 20·log(rms) to obtain an rms pressure level. Since the results are identical, the terms "SPL," "rms pressure level," and "mean-square pressure level" are used interchangeably.

Implicit in any stated sound level is the range of frequencies represented therein. Signal energy at frequencies outside this ***analysis bandwidth*** is not included in the stated value. In cases where significant sound energy lies outside the analysis bandwidth, computed SPL values will be less than if a wider analysis bandwidth had been used. To avoid this effect, SPL measurements are often made over very large analysis bandwidths, such as 5 Hz to 10 kHz, to be sure of including all relevant signal energy. The result is called ***broadband*** SPL. Unfortunately, by incorporating nearly all acoustic energy in the spectrum, broadband SPL may be influenced by sounds other than the one under investigation.

To understand how sounds at different frequencies contribute to a signal being studied, SPL values are often computed and plotted on a per-unit frequency basis (that is, per hertz). Such levels are called ***spectrum levels*** or ***spectral density levels***, and carry units of dB re 1 $\mu Pa^2/Hz$. Graphs of spectral density vs. frequency present much of the amplitude and frequency information available about an acoustic signal.

One-third octave band analysis offers a convenient compromise between broadband SPL levels on the one hand and spectral density plots on the other. One-third octave bands are frequency bands whose upper limit in hertz is $2^{1/3}$ (1.26) times the lower limit; the width of a given band is 23% of its center frequency. The higher the center frequency of the band, the wider its bandwidth. For example, the 1/3-octave band centered at 16 Hz extends from 14.1 to 17.8 Hz, whereas the band centered at 160 Hz extends from 141 to 178 Hz. The 1/3-octave band level is calculated by integrating the spectral densities between the band frequency limits. Conversion to decibels [10·log(sum of squared pressures in the band)] gives the 1/3-octave band level.

A sound's temporal characteristics may play as important a role in its effect on listeners as its amplitude and spectrum. For example, a strong sound that occurs occasionally may affect listeners less than a weaker sound that is continually present, challenging attempts to label a sound with a single measure of its potential for disturbance. Exacerbating this challenge, physical measures used to quantify transient sounds (such as impact pile driving) tend to be less meaningful when applied to continuous sounds (such as vibratory pile driving) and vice-versa. Specifically, transient sounds are often described in terms of their ***instantaneous peak amplitude*** and an integrated measure of energy contained in each sound pulse known as ***sound exposure level*** or ***SEL***. Neither of these metrics applies well to continuous sounds. The instantaneous peak amplitude of a continuous signal simply indicates the "top" of the continuous waveform rather than its average amplitude, conveying little additional information about the signal. A measurement of instantaneous peak amplitude during a relatively quiet continuous sound may confuse interpretation by capturing a sporadic unrelated event such as the drop of a hammer. SEL is likewise unhelpful for a continuous sound because, as an integrated measure of total acoustic energy received, it rises without limit as the sound persists.

3 METHODS

Field recordings took place on 11 November 2004 and encompassed the driving of two complete piles (piles “S3U” and “S3D”) at the Snohomish River crossing of Pipeline 5, located at N 47°56.92′ W 122°11.07′ (WGS 84 datum).

3.1 OPERATION OF VIBRATORY DRIVER

Advanced American Diving (AAD) Service, Inc. of Oregon City, Oregon, drove all piles using an American Piledriving Equipment (APE) model 200 vibratory driver/extractor (Figure 1). All piles were 14-inch-wide 14-119 steel H-piles (119 indicates the weight in pounds per foot of pile length). Each pile was driven in two segments, a primary segment 70 ft long and a secondary segment (called a “stinger”) 40–50 ft long. Driving on 11 November proceeded as follows:

1. The primary segments of piles S3U and S3D were driven until only a few feet of the piles remained exposed above the waterline.
2. The secondary segment for S3U was welded onto the exposed tip of the primary segment.
3. Pile S3U was driven to final depth, about 60 ft into the riverbed (embedment depth).
4. Any unnecessary remainder of Pile S3U above the pipeline was removed with an underwater chainsaw.
5. Steps 2–4 were repeated with Pile S3D.

Table 1 gives the times during which vibratory driving for each pile segment took place. Figure 2 shows the configuration of the driving site, showing Pile S3U after its primary segment had been driven but before its secondary segment was welded on.

The APE 200 vibratory driver was capable of adjustable drive power. For most of the day the driver ran at approximately 50% power, which the operators indicated was typical. To overcome resistance while driving the secondary segment of Pile S3U, however, the operators found it necessary temporarily to increase power to about 60% of maximum.

TABLE 1. Vibratory driving activity on 11 November 2004.

Pile	Segment	Time Started PST	Time Finished PST	Total Time min	Time driver on min
S3U	Primary	10:30	10:54	24	11
S3D	Primary	11:50	12:12	22	10
S3U	Secondary	13:45	13:53	7	7
S3D	Secondary	14:04	14:23	19[a]	11[a]

[a] Operators frequently interrupted this drive to accommodate boat-based measurements

Figure 1. Vibratory driver. An APE Model 200 vibratory driver/extractor drove all piles during construction. It is shown driving the primary segment of pile S3U.

Figure 2. Driving configuration. Driving of the primary segment of pile S3U (light-colored pile closest to crane) has been completed, and the crew is preparing to drive the primary segment of pile S3D.

3.2 DATA ACQUISITION

Greeneridge employed five different hydrophone sensors to acquire acoustic data. Table 2 lists the hydrophones and their characteristics. Two of the hydrophones (the ITC 1032 and 1042) were suspended over the side of a small landing craft provided and operated by AAD. These "boat-based" hydrophones enabled measurements to be made at a variety of locations while allowing Greeneridge staff to monitor recording quality. The ITC 1042 hydrophone was deployed at 3-ft (1-m) depth while the ITC 1032 hydrophone was deployed about 3 ft (1 m) above the riverbed; actual depth of the ITC 1032 therefore depended on water depth. The two boat-based hydrophones were cabled to amplifiers and thence to a Sony PC208Ax DAT-based digital instrumentation recorder. This recorder sampled the acoustic waveforms from each hydrophone at a 48-kHz rate and with 16-bit resolution, providing a recorded spectrum of below 5 Hz to 20 kHz and a dynamic range of over 90 dB. Greeneridge staff adjusted amplifier gains for best signal levels in real time to ensure optimum use of the available dynamic range. All boat-based equipment operated on battery power.

The remaining three hydrophones were embedded in small self-contained acoustic recorders known as "Bioacoustic Probes." These autonomous recorders were designed by one of the authors (WCB) and are manufactured by Greeneridge Sciences. The three Bioacoustic Probes were programmed at their least-sensitive gain setting and deployed on the riverbed before driving commenced. The autonomous recordings covered a spectrum of 8 Hz to 2 kHz; however, driver-related and ambient sounds above 100 Hz received by the Bioacoustic Probes were quiet enough to be below internal instrumental noise. Use of these data was therefore limited to frequencies below 100 Hz.

A fourth Bioacoustic Probe, designed to measure weaker signals than the others, was brought as a spare. This unit was deployed on the riverbed at a depth of 18 ft (5.5 m) and a range of 66 ft (20 m) from the vibratory driver for the latter half of the monitoring effort. Unfortunately it proved unable to provide complete quantitative data from this location, as the sound levels received by this unit usually exceeded its maximum limit of 167 dB broadband SPL (the saturation level for the spare unit was 19 dB lower than that of the others). Data from this unit are thus discussed only briefly in this report.

Acoustic recordings took place at eleven stations (Table 3). The stations were categorized as either "drift" or "fixed." For drift stations, the monitoring vessel was driven to the desired

TABLE 2. Hydrophones.

Hydrophone	How deployed	Nominal sensitivity dB re 1 V/µPa
ITC 1032	From boat, typ. 3 ft (1 m) above riverbed	-194.0
ITC 1042	From boat, 3 ft (1 m) below surface	-204.0
Bioacoustic Probe B008	On riverbed	-190.8
Bioacoustic Probe B012	On riverbed	-190.6
Bioacoustic Probe B022	On riverbed	-190.8

area, stopped, and then allowed to move with the current. Engines were turned off and the crew was instructed to avoid unnecessary talking or moving about the vessel. Although currents in this part of the Snohomish River have been known to exceed 8 ft/s, currents at the time of these drift-station recordings were nearly imperceptible.

The fixed stations consisted of the 46-ft (14-m) boat-based site and the three autonomous-recorder sites. The fixed boat-based station (Station FB) was monitored by tying the recording vessel to one of the operations barges. The fixed Bioacoustic-Probe stations (stations F1, F2, and F3) were deployed with each instrument resting unweighted on the riverbed (the Bioacoustic Probes are negatively buoyant). To allow recovery, a 1/4" nylon line ran from each instrument to an 18-lb toothed mushroom ("river") anchor, and on to a 15-inch 65-lb white marker buoy.

Figure 3 maps the locations of the recording stations shown in Table 3 relative to the piles and to the banks of the Snohomish River. Note that drift stations D1, D2, and D3 were chosen to be very close to fixed stations F1, F2, and F3, respectively. This configuration allowed comparison of boat-based measurements with those from the autonomous recorders. Note also that Station D7, where recordings were made of ambient sounds when the vibratory driver was off, was located around a bend in the river from the project site. This location ensured minimum contamination from other machinery at the site. Figure 4 shows the drive location and indicates the marker buoys for stations F1, F2, and F3.

Positions for the monitoring vessel were determined using a Garmin GPS 12MAP handheld GPS receiver. For the autonomous recorders, positions were estimated from the monitoring vessel's GPS location at the time the instrument package was lowered into the water; due to currents at deployment time, however, the instruments may not have reached the riverbed at precisely the marked location. Ranges to the vibratory driver were obtained from a Bushnell "Yardage Pro Compact 800" laser rangefinder. Water depths were obtained

TABLE 3. Recording stations.

Station	Type	Recorder	Range to Piles[a] ft (m)	Water Depth ft (m)	Hydrophone Depth[b] ft (m)	Description
FB	Fixed	Boat-based	46 (14)	18 (5.5)	15 (4.5)	Tied up to dive barge
F1	Fixed	Probe	233 (71)	16 (4.8)	16 (4.8)	On riverbed
F2	Fixed	Probe	548 (167)	15 (4.7)	15 (4.7)	On riverbed
F3	Fixed	Probe	1050 (320)	18 (5.4)	18 (5.4)	On riverbed
D1	Drift	Boat-based	262 (80)	11 (3.5)	8 (2.5)	Upriver, near F1
D2	Drift	Boat-based	627 (191)	10 (3.0)	7 (2.0)	Upriver, near F2
D3	Drift	Boat-based	1116 (340)	15 (4.5)	11 (3.5)	Upriver, near F3
D4	Drift	Boat-based	213 (65)	15 (4.5)	11 (3.5)	Adjacent to site
D5	Drift	Boat-based	282 (86)	18 (5.5)	15 (4.5)	Downriver
D6	Drift	Boat-based	696 (212)	18 (5.5)	15 (4.5)	Downriver
D7	Drift	Boat-based		26 (8.0)	23 (7.0)	Ambient

[a] For drift stations, the range given is representative for the measurements quoted in this report
[b] For deep hydrophone or riverbed recorder; the shallow hydrophone was always at 3-ft (1-m) depth

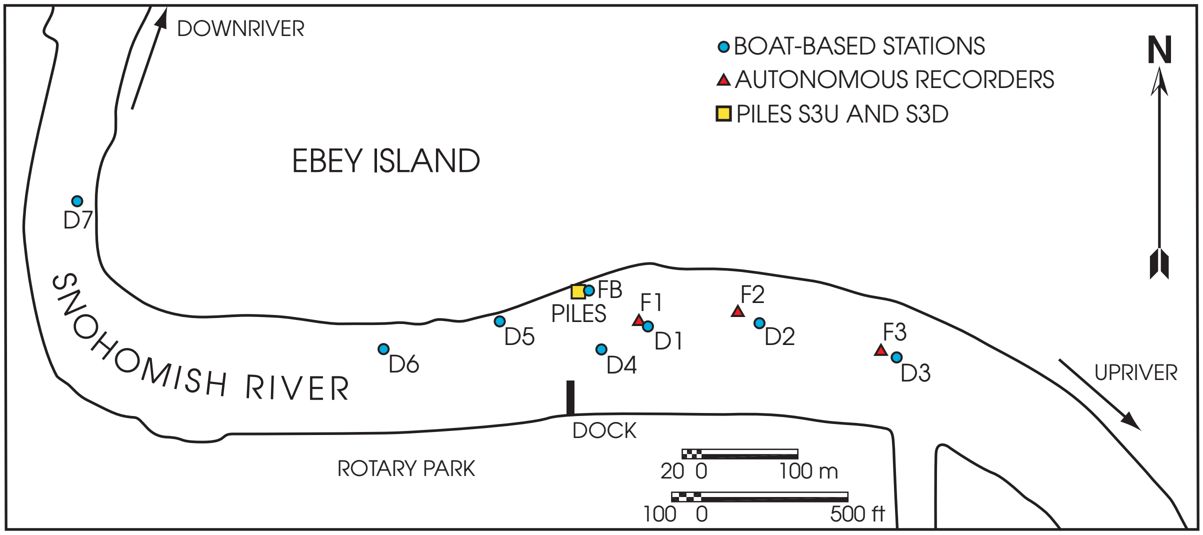

Figure 3. Site map.

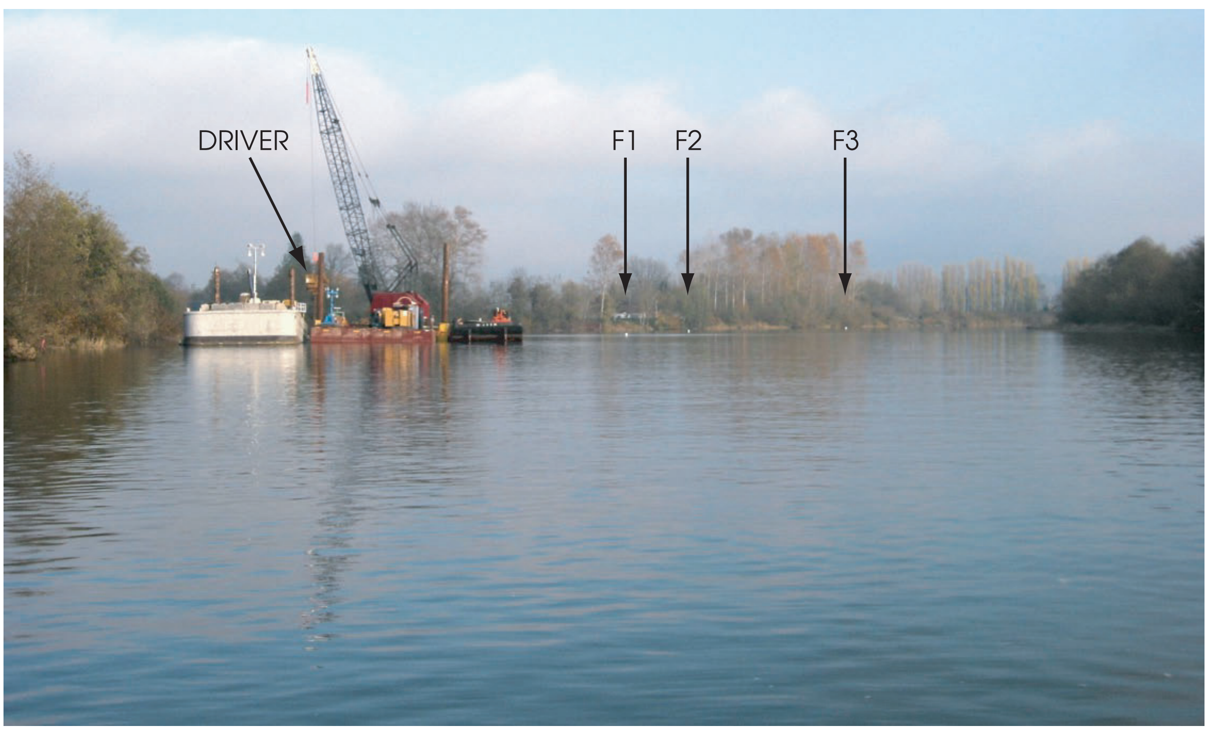

Figure 4. Construction site looking east from Station D6. Arrows indicate buoys marking fixed-recorder sites F1, F2, and F3.

by mechanically sounding the river, either with the hydrophone string or with the mushroom anchors used to deploy the autonomous recorders. Note that water depths in the river are affected by tides and recent rainfall; the depths stated here are those determined at the time of the measurements.

3.3 DATA ANALYSIS

After acquisition, all acoustic data were digitally transferred to desktop computers running custom analysis software. Boat-based data were calibrated for the specific hydrophones used and high-pass filtered at 4 Hz to remove offsets and low-frequency artifacts associated with motion of the monitoring vessel. Bioacoustic-Probe data were filtered above 8 Hz by the acquisition hardware.

To estimate spectral densities of a selected data section, the section was first detrended and then split conceptually into a series of overlapping segments. Each segment was windowed (using a three-term Blackman-Harris window) and transformed into the frequency domain using a Fast Fourier Transform (FFT). The transforms of the segments were then averaged together to form a representative spectrum. Narrowband spectral densities were estimated using a frequency resolution of 0.7 Hz, while a resolution of 12 Hz was used for wideband spectral densities.

One-third octave band levels for selected data sections were estimated by subtracting the mean of each section, then applying a Blackman-Harris window and FFT over the entire section. The transformed values were then summed into appropriate one-third octave bands. As a consistency check the sum of all one-third octave bands was compared with the mean-subtracted rms level calculated directly from the time series.

To assess variability with time, acoustic recordings of the vibratory driver were partitioned into overlapping segments of 1 s each. Spectral processing of each segment yielded both the broadband SPL and the SPL in a selected one-third octave band for that 1-s segment. The analysis segments overlapped by a factor of nine-tenths, that is, each new segment was shifted in time by 0.1 s from the previous segment. This process produced two time series, effectively sampled at 10 Hz, representing the fluctuation of broadband and one-third octave band SPL.

The resulting data were plotted as a function of time to show fluctuations in received level and to identify the maximum broadband and one-third octave band SPL values received. The time series were also used to determine average level during periods of sustained driver activity. To accomplish this, selected samples from the time series were converted from decibels into squared amplitude values, averaged to find a mean squared amplitude value, and the result converted back into decibels.

4 RESULTS AND DISCUSSION

4.1 CHARACTERISTICS OF SOUNDS RECEIVED FROM THE VIBRATORY DRIVER

Analysis focused on the following aspects of the sounds generated by the vibratory driver:

- the frequency spectrum close to the source;
- dependence of the spectrum on range and receiver depth;
- dependence of received level on time, pile depth, and driver frequency; and
- dependence of received level on range to the driver.

In the reporting and discussion of these results, all mention of sound levels refers to the acoustic pressure levels physically measured by the hydrophones, not to particle motion. Section 4.2 discusses the relationship of these measurements to particle motion.

4.1.1 Frequency characteristics and comparison with ambient noise

The APE model 200 vibratory driver and H-pile configuration radiated sound underwater consisting of an infrasonic tone with several harmonics, as shown in Figure 5 for a range of 46 ft (14 m). At the deep hydrophone, where the sounds from the vibratory driver were strongest, the infrasonic tone was over 30 dB stronger than any of its harmonics or other associated sounds. For the period shown, this single tone accounted for over 89% of the total acoustic pressure present.[†] The tone's frequency varied between 12 and 18 Hz during normal operation but typically lay within the 14.1 and 17.8-Hz boundaries of the 16-Hz one-third octave band. For most of our analysis, therefore, sounds associated with the driver were determined in the one-third octave band centered at 16 Hz. Excluding frequencies outside the driver's one-third octave band removed contamination from unrelated sounds while preserving all of the acoustic pressure present in the driver's infrasonic tone. This was especially important at longer ranges and at shallow depths, where the driver signal was relatively weak.

Comparison of the spectrum from the shallow and deep hydrophones at Station FB (Figure 5, lower panels) suggests that, while the infrasonic tone and its harmonics were received more strongly with increasing depth, no such rule could be applied to the wideband noise associated with driving operations. This finding is consistent with a near-field environment where narrowband, low-frequency sound from the vibrating pile coupled into

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[†] This percentage was calculated from the square root of the ratio of mean-square pressure within the 16-Hz one-third octave band (155 dB re 1 µPa in this example) to broadband mean-square pressure (156 dB). The ratio of mean squares, 79%, corresponds to the ratio of mathematical power present in the narrowband and broadband pressure waveforms and acousticians would generally use that value here rather than its square root. Because the sound field in the Snohomish River was complex, however, mathematical power in the pressure waveforms may not accurately reflect physical power in the acoustic wave. We have stated values in terms of pressure amplitude to avoid confusion between mathematical power and physical power.

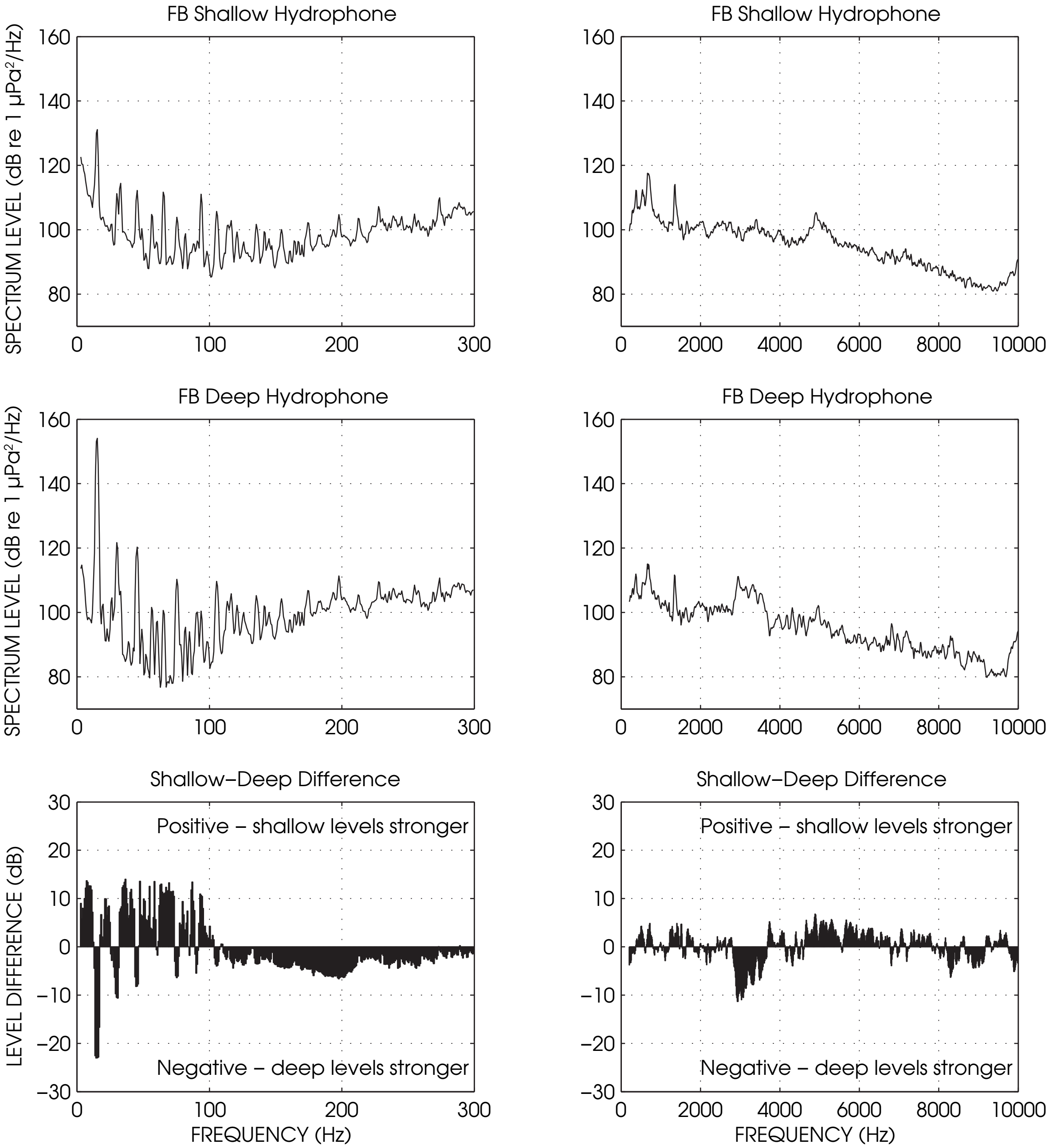

Figure 5. Spectral densities at 46-ft (14-m) range. The graphs show levels obtained at Station FB averaged over a 60-s period during driving of the secondary segment of pile S3U. The left-hand panels, prepared with a resolution of 0.7 Hz, show a 15.2-Hz fundamental frequency radiated by the driver as well as several harmonics. The right-hand panels were prepared with a resolution of 12 Hz to show frequency-averaged broadband noise. While the narrowband tones evident in the left-hand panels are not visible in the right-hand panels, their acoustic content is included.

the water from the riverbed below, while wideband, high-frequency sound from the associated machinery (see Figure 2) coupled into the water from the barges above.

Figure 6 plots a one-third octave band representation of the near-field spectrum received at Station FB. The infrasonic tone dominated all other bands at the deep hydrophone, while at the shallow hydrophone its contribution was not only weaker than that of several other bands (upper panel) but 23 dB weaker than at the deep hydrophone (lower panel).

Other sound sources located at the project site included a crane, compressors, and movement of the work barges within a framework of beams, called "spuds," that may have conducted some sound into the riverbed (see Figure 2). The data indicate that the sound contribution from these sources was negligible compared with that from the driver.

Ambient noise

Also displayed in Figure 6 are levels corresponding to ambient sounds recorded at Station D7 at a time of minimal current and no vessel activity. These one-third octave band levels ranged from below 70 to just over 90 dB re 1 µPa. Levels in this range are considered quiet. For example, the ambient level in the 25-Hz band (deep hydrophone) was 84 dB re 1 µPa; in comparison, *Burgess and Blackwell* [2003] measured ambient 25-Hz band levels in the industrialized Duwamish River (south of Seattle) at 100 to 116 dB re 1 µPa.

The ambient sound levels observed at Station D7 may have been atypically quiet. Strong continuous background noise would be expected during times of heavy river flow. Transient sounds from tugboats, barges, and pleasure craft would also be common, and indeed a launching dock for recreational vessels was located opposite the construction site. An opportunistic recording of a tugboat accelerating and pushing a barge near the site was made using a Bioacoustic Probe lowered to the riverbed at the end of the dock; the broadband received level at a range of approximately 130 ft (40 m) reached a maximum value of 146 dB re 1 µPa in a 1-s period and a sustained average of 137 dB over a period of 50 s. While more detailed analysis of the tugboat sounds lies beyond the scope of this effort, these received levels were comparable to those from the driver at similar range and suggest that ambient sound levels in the Snohomish River may routinely exceed those recorded at Station D7.

4.1.2 Dependence of spectrum on range and receiver depth

During driving of the primary segment of Pile S3D, recordings were made at three drift stations (D1, D2, and D3) near the autonomous riverbed recorders (F1, F2, and F3, respectively). These recordings allowed comparison of received levels and spectra at three depths and at three ranges. Figure 7 summarizes the results of this comparison. The figure also includes ambient levels for the shallow and deep boat-based hydrophones from Station D7.

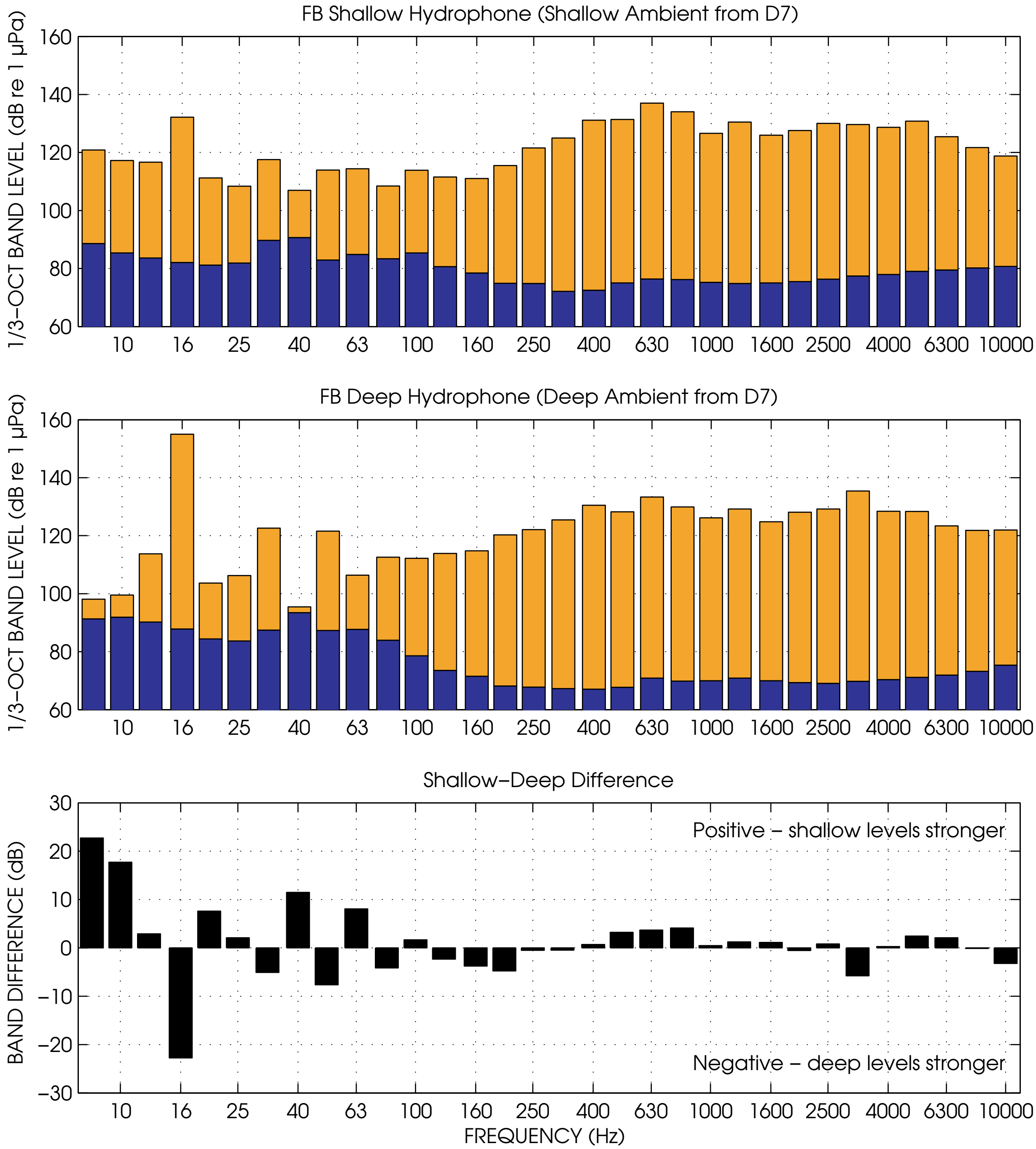

Figure 6. One-third octave bands at 46-ft (14-m) range. The upper (orange) portion of each bar indicates a level obtained at Station FB averaged over a 60-s period during driving of the secondary segment of pile S3U. The lower (blue) portion of each bar indicates an ambient level obtained during a 30-s period around a bend in the river from the drive site, at a time when no driving was underway.

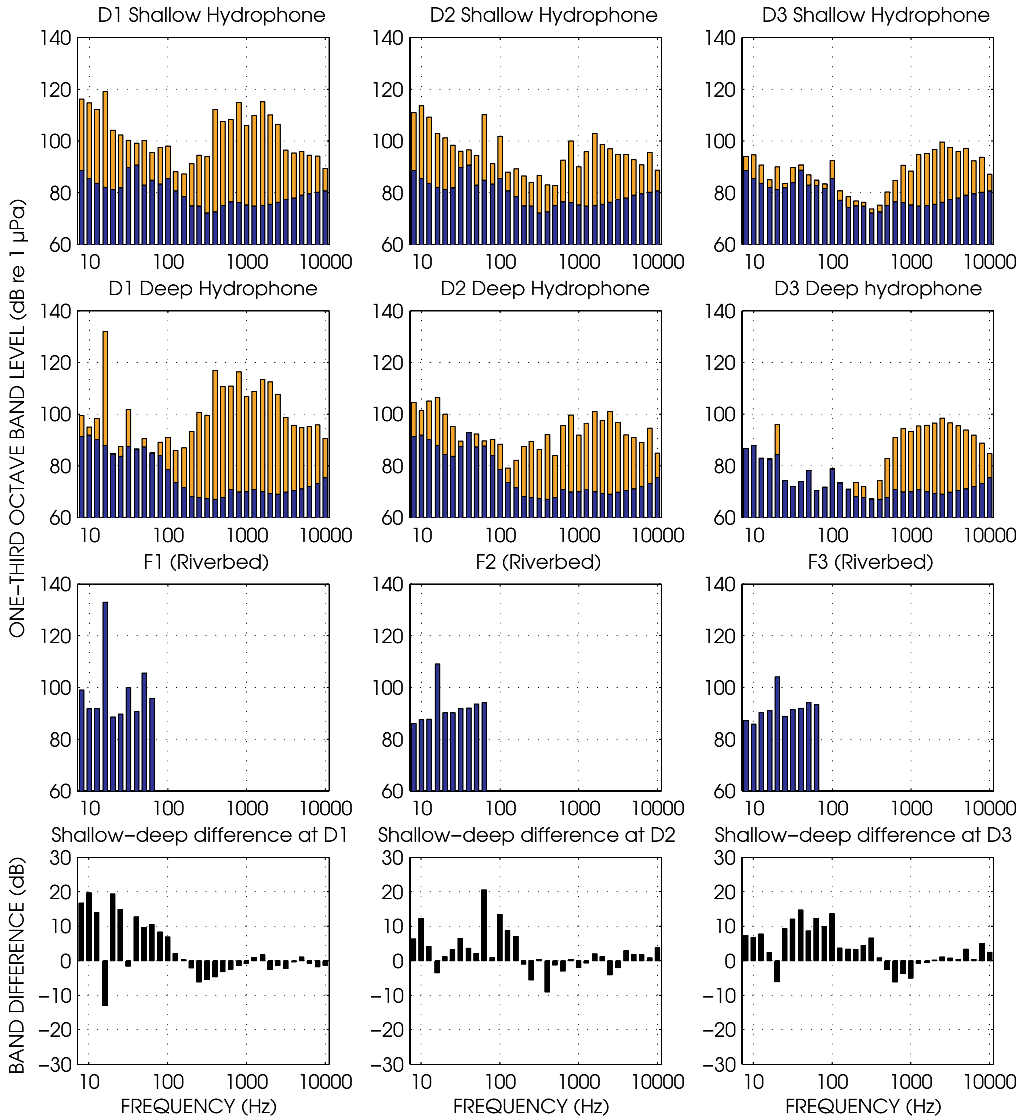

Figure 7. One-third octave bands at stations D1/F1 (233–262 ft), D2/F2 (548–627 ft), and D3/F3 (1050–1116 ft). Each panel reflects data averaged over a 15-s period during driving of the primary segment of pile S3D. For each range (i.e. within each vertical column of panels) data were selected from the identical time period to facilitate comparison of received levels at different depths. As in Figure 6, the upper (orange) portion of each bar indicates a level received during driving, while the lower (blue) portion of each bar indicates an ambient level. In a few instances where levels measured during driving fell below those measured at the ambient station, the graphs show undivided (blue) bars that correspond to the levels measured during driving. Levels from the riverbed recorders are represented only by undivided (blue) bars and are shown only below 100 Hz because of increasing instrumental noise at higher frequencies. Note that although the driver's fundamental frequency typically lay in the 16-Hz band, during recordings at Station D3 it lay in the 20-Hz band.

The boat-based data shown in Figure 7 suggest that, within the water column at least, higher frequencies associated with driving activity persisted with increasing range more effectively than the infrasonic tone from the vibrating pile. This observation is consistent with the "waveguide cutoff" effect, in which the shallowness of a body of water prevents propagation of frequencies below a "cutoff frequency" that depends on the water depth. Deeper water is capable of carrying lower-frequency acoustic waves. The phenomenon is analogous to a guitar string that cannot vibrate below a certain frequency that is determined by its length, composition, and tension.

A different situation emerges from the riverbed-recorder data. Figure 7 shows that, unlike the boat-based hydrophones, the riverbed recorders clearly observed the fundamental tone of the vibratory driver at least 10 dB above the surrounding noise out to a range of 1050 ft (320 m). Table 4 lists one-third octave band levels for the fundamental tone as received simultaneously across hydrophones at each station pair D1/F1, D2/F2, and D3/F3. Levels received at the riverbed were always higher than at the shallow or deep hydrophones. At station pair D3/F3 the driver's one-third octave band level was 8 dB greater on the riverbed than at the deep hydrophone.

The strength of the infrasonic vibratory-driver tone on the riverbed relative to that in the water suggests that the riverbed itself conducted acoustic energy from the driver. Because the river was too shallow to support propagation of the infrasonic tone within the water column, the sound field in the water consisted only of a boundary wave associated with the riverbed that diminished rapidly with height above the bottom. This effect appears to have been true even at close range to the driver; the spare Bioacoustic Probe deployed on the riverbed at 66-ft (20-m) range regularly experienced broadband SPL above 167 dB, its saturation limit for the signal in question, even though the deep boat-based hydrophone never received broadband levels higher than 161 dB.

TABLE 4. Simultaneously received[a] shallow, deep, and riverbed one-third octave band levels.

Station	Range ft (m)	Center freq. Hz	Comparison time s	Shallow dB re 1 µPa	Deep dB re 1 µPa	Riverbed dB re 1 µPa
D1/F1	233–262 (71–80)	16	15	119	132	133
D2/F2	548–627 (167–191)	16	15	103	106	109
D3/F3	1050–1116 (320–340)	20[b]	15	90	96	104

[a] Simultaneous reception was across depths at each station, not between stations
[b] Fundamental frequency of driver was 18.0 Hz, falling in the 20-Hz one-third octave band

4.1.3 Received levels as a function of time, pile depth, and driver frequency

Figure 8 shows how received levels in the 16-Hz one-third octave band fluctuated with time for each of the four driving segments monitored, as observed at the F1 autonomous recorder at 233-ft (71-m) range. No distinct pattern emerges from the graph, suggesting that factors other than pile depth dominated the variation of received level with time.

To determine if the character of the time dependence shown in Figure 8 applied at other ranges, data simultaneously recorded at stations FB (deep hydrophone), F1, F2, and F3 were compared over an 87-s interval (Figure 9). The figure shows a surprising lack of conformity between the four stations. When Station FB saw a gradual rise in received level in the second half of the graph, for example, the other stations saw a gradual decline. In the middle of the graph, a decline at Station FB corresponded to a rise at stations F1 and F3 but only a transient rise at Station F2. Finally, the received level at Station F2 was often weaker than at Station F3, at one point by as much as 29 dB, despite F2 being half F3's distance from the pile. These data suggest that the cylindrical-spreading model customary for analysis of propagation in shallow water does not apply well in this situation. That model predicts a steady gradual decrease in received level with range, but the data do not support this.

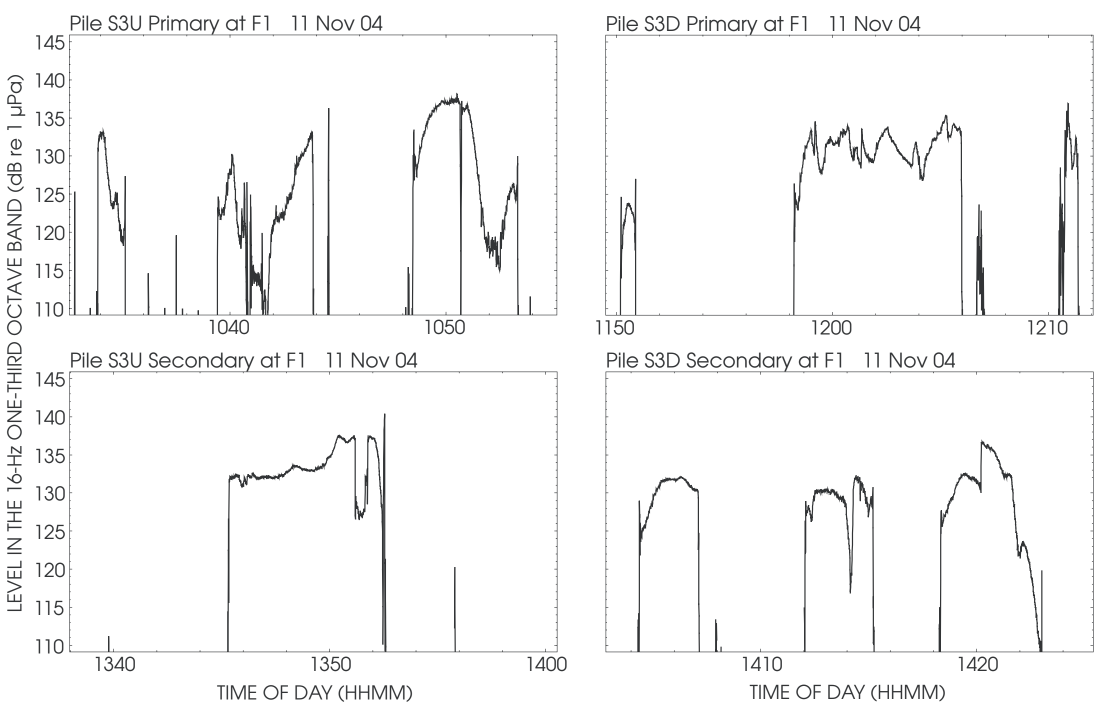

Figure 8. Fluctuations in the 16-Hz one-third octave band level at Station F1 during driving. Primary piles were driven 40–50 ft into the riverbed. Secondary driving embedded each pile to a final embedment depth of about 60 ft into the riverbed. The longest uninterrupted period of driving lasted 8 min (upper-right panel).

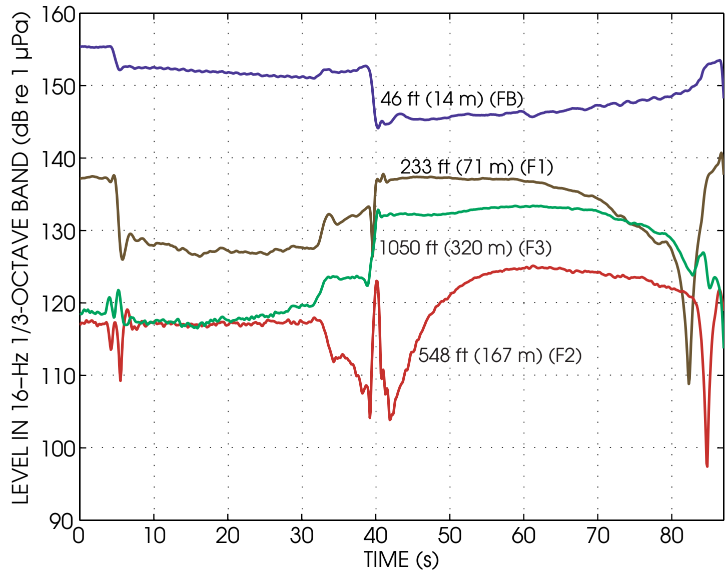

Figure 9. Variation of received level with time at different ranges. The graph shows simultaneous fluctuations of received level measured at four different ranges. Data from Station FB were obtained from the deep hydrophone. Zero seconds corresponds to 13:51:00, during driving of the secondary segment of Pile S3U.

A key to this puzzle lies in remembering that the frequency of the vibratory driver was not fixed. While it generally remained inside the 16-Hz one-third octave band, within that band it varied. At zero seconds in Figure 9, the fundamental frequency of the vibratory driver was 14.3 Hz. At 5 s it rapidly increased to 15.4 Hz, corresponding to the drop in received levels at stations FB and F1. At 40 s it increased again to 16.8 Hz. From there the fundamental frequency gradually declined, reaching 13.9 Hz at the very end of the graph (just outside the 16-Hz one-third octave band). As the graph shows, each of these shifts in frequency was accompanied by a change in received level at each station, though the direction and extent of the change was not uniform across all stations. Such significant changes in received level associated with changes in source frequency indicate that the acoustic field in the riverbed and river was complex, possibly involving an imperfect standing wave or an interfering combination of outgoing waves.

4.1.4 Maximum received levels

Variability and complexity characterized the received levels measured in this effort. Figure 10(*a*) summarizes these aspects for levels received at the deep hydrophone and the riverbed recorders. Variability of all levels received ranged over nearly 70 dB, while variability at several individual stations ranged over 30 dB. Complexity included the potential for received levels at longer ranges to be greater than those at shorter ranges (Figure 9).

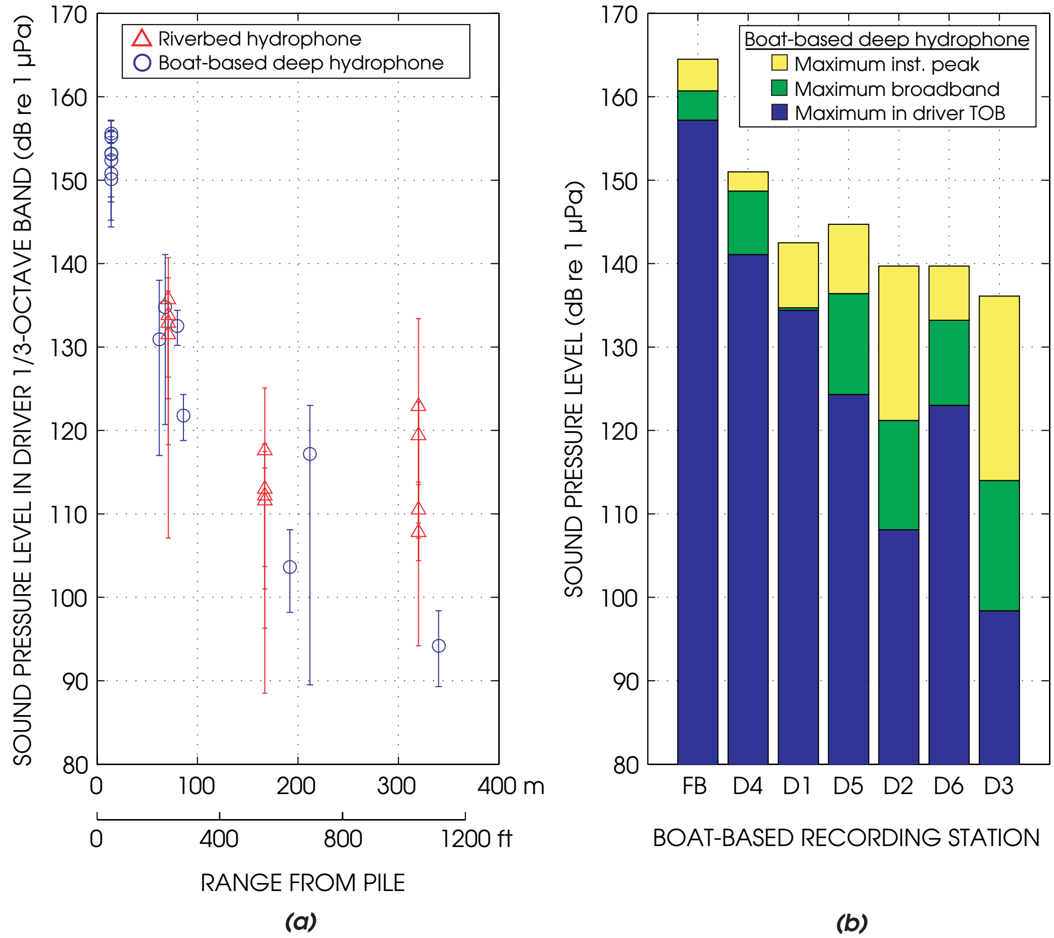

Figure 10. Range-dependence of one-third octave band levels, and comparison with maximum broadband and instantaneous peak values. One-third octave band (TOB) levels for both panels were calculated in the 16-Hz band at all stations except D3 at 1116-ft (340-m) range, where the 20-Hz band was used. Panel (*a*) shows the variability of received levels at the deep and riverbed hydrophones. Each plot symbol denotes the mean level of a separate data period selected as representative of the different pile segments or of different monitoring locations. Panel (*b*) compares maximum one-third octave band levels with maximum broadband levels and maximum instantaneous peak amplitudes at the deep hydrophone, ordered by increasing distance from the driver. Panel (*a*) does not include transient levels occurring when the driver was turned off and its frequency passed through an apparent resonance below the 16-Hz band. Broadband and peak values depicted in Panel (*b*) represent all boat-based measurements from the deep hydrophone, including driver-shutoff transients.

To simplify interpretation, we will focus only on maximum levels received by the deep hydrophone at each boat-based measurement site. These levels are listed in Table 5 and graphed in Figure 10(*b*). Because deep-hydrophone levels associated with the infrasonic tone always exceeded corresponding shallow-hydrophone levels, the maximum deep-hydrophone results represented the strongest levels in the majority of the water column located between the surface and 3 ft (1 m) above the riverbed. While levels within 3 ft (1 m) of the riverbed may have been greater, this region of potentially increased exposure constituted a small percentage of the total volume of water available to swimming fish. Fish that naturally chose a deep or riverbed habitat, however, may have experienced disproportionate exposure. This effect is discussed further in the following section (§4.1.5).

To interpret the maximum levels in Table 5 and Figure 10(*b*) requires an understanding of how to compare one-third octave band, broadband, and instantaneous peak measurements. Section 2.1 introduced these concepts. To review them in the context of this effort:

The ***16-Hz one-third octave band level*** represents all of the acoustic pressures recorded whose frequencies were between 14.1 and 17.8 Hz. At least 89% of the acoustic pressure coupled by the vibratory driver into the river, as measured on the deep hydrophone at 46-ft (14-m) range, was concentrated in an infrasonic tone that usually lay inside this band. When the tone was both inside the 16-Hz one-third octave band and strong relative to other sounds in the spectrum, the 16-Hz band level and the broadband level were nearly identical, the broadband level being only slightly higher due to the contribution of extraneous sounds. During measurements at Station D3, the driver's infrasonic tone occupied the 20-Hz one-third octave band, so that levels from that band were used in Table 5 and Figure 10.

The ***broadband level*** represents all of the acoustic pressures recorded across all frequencies from 4 to 10,000 Hz. It includes not only the infrasonic tone from the driver but also sounds from other machinery, both related and unrelated to the driving, and local artifacts such as ripples slapping on the underside of the monitoring vessel's hull. At close range to

TABLE 5. Strongest signals received at the deep boat-based hydrophone.

Station	Range ft (m)	Max. Sustained TOB^{a,b} dB re 1 µPa	Duration^{c} s	Max. TOB^{a,b,d} dB re 1 µPa	Max. Broadband^{a,d} dB re 1 µPa	Max. Peak^{d} dB re 1 µPa
FB	46 (14)	156	79	157	161	164
D1	262 (80)	132	28	134	135	142
D2	627 (191)	104	30	108	121	140
D3	1116 (340)	94	14	98	114	136
D4	203 (62)^{e}	135	152	141	149	151
D5	282 (86)	122	90	124	136	145
D6	696 (212)	117	193	123	133	140

^{a} Calculated from RMS values determined over one-second intervals
^{b} All in the 16-Hz one-third octave band (TOB) except D3 in the 20-Hz TOB
^{c} Duration over which sustained RMS value shown was averaged
^{d} Strongest of all values recorded for the station
^{e} Mean band and maximum instantaneous peak values recorded at 223-ft (68-m) range

the driver, the driver's infrasonic tone dominated all other sounds and the broadband level was nearly identical to the level in the one-third octave band containing the tone.

The ***instantaneous peak amplitude*** represents the most extreme point received on the acoustic pressure waveform. Researchers often employ this measure to describe strong transient events such as impact pile driving. For weaker but continuous sounds such as vibratory pile driving it is less useful, being easily contaminated by unrelated events like a single hammer blow on a nearby barge. When no such contamination takes place, the instantaneous peak amplitude of a strong continuous signal is typically 3–5 dB greater than the broadband level; the broadband level is lower because it is calculated from a root-mean-square average of the waveform rather than from its peaks (§2.1).

In addition to these values, Table 5 includes ***maximum sustained TOB*** or maximum sustained third-octave band level. This value represents an average of 1-s mean-square values in the driver's one-third octave band (20 Hz for Station D3, 16 Hz for all others). Each average was taken over a period selected to include the strongest levels observed at the given station while excluding breaks in operation and unrelated transients. For example, the first line of Table 5 indicates that the strongest sustained level received at Station FB occurred during a 79-s period in which levels in the 16-Hz one-third octave band averaged 156 dB re 1 µPa. Thus, where the "maximum TOB" and "maximum broadband" columns in Table 5 indicate maximums that occurred over only a one-second time span, this column provides information on the strongest sustained levels encountered.

To interpret Figure 10(*b*) in terms of these measures, first we consider the levels in the driver's one-third octave band. These are identical to the upper bounds of the range bars plotted in Figure 10(*a*). They indicate that, up to about 282 ft (86 m) from the vibratory driver, levels received from the driver appeared to decline monotonically with distance. At 548 ft (167 m) and above, maximum levels received from the driver followed no clear pattern but at the deep hydrophone were never stronger than 123 dB re 1 µPa.

As required mathematically, maximum broadband levels were always stronger than the levels in the driver's one-third octave band. At stations FB and D4 the maximum broadband levels of 161 and 149 dB, respectively, resulted from the infrasonic tone of the driver when it passed through a frequency below the 16-Hz one-third octave band during shutdown. Specifically, when the driver was turned off, its frequency decreased through what appeared to be a resonance near 6 Hz for 1–3 s. The maximum broadband measure at FB and D4 captured the brief increase in received level resulting from this apparent resonance. At Station D1, the maximum broadband level was only marginally stronger than the maximum level in the 16-Hz one-third octave band (the data acquired at D1 included no startup or shutdown transients).

At the more distant stations maximum broadband levels were 10–15 dB greater than maximum levels in the driver's one-third octave band. This indicates that sounds from sources besides the driver contributed significantly at those stations. This is consistent with the far-field spectra (Figure 7) showing that higher-frequency components associated with driving activity dominated the spectrum at longer ranges. These components may have been produced from driver machinery, or possibly by other machinery operating at the drive site.

Maximum instantaneous peak amplitudes at stations FB and D4 were, as expected, only a few decibels above the maximum broadband levels. At longer ranges, however, maximum instantaneous peak amplitudes appeared independent of broadband levels. This suggests that isolated sounds associated with construction, or possibly artifacts local to the monitoring vessel, led to the peak amplitudes detected at greater ranges from the driver.

4.1.5 Zone of exposure to SPL above 150 dB

The U.S. Fish and Wildlife Service and NOAA Fisheries use 150 dB re 1 µPa SPL as a general guideline threshold to evaluate potential impacts of sound on the behavior of most species of fish, including salmonids within the project area. Therefore a goal of this effort was to estimate what portions of the Snohomish River may have experienced levels above 150 dB.

Typical models for sound exposure in shallow water begin with the assumption that sound spreads outwards from the source in a cylindrical fashion. Spreading of the acoustic wavefront over this growing cylindrical surface causes a gradual and steady decrease in received level with range. The levels received from the vibratory driver in the present case, however, are not consistent with this model. Instead, it appears that primary sound conduction took place in the riverbed. Sound in the river was limited to an acoustic boundary wave extending upwards from the riverbed, with the strongest levels occurring along the river bottom.

Figure 11 depicts the maximum estimated zone of exposure to levels above 150 dB re 1 µPa. The height of the 150-dB threshold at 46-ft (14-m) range (Station FB) was determined by interpolation between the maximum 16-Hz one-third octave band levels obtained at the shallow and deep hydrophones for that station. For more distant stations, the threshold height was determined by interpolation between the maximum 16-Hz one-third octave band levels as measured at the deep hydrophone and as estimated at the riverbed by adding 15 dB to the deep-hydrophone level. This 15-dB constant was based on the greatest difference observed between maximum levels at the riverbed and at 3-ft (1-m) height: the spare Bioacoustic Probe on the riverbed at 66-ft (20-m) range recorded levels a few dB over its saturation at 167 dB, approximately 15 dB greater than the 156-dB maximum sustained level recorded at the nearby Station FB deep hydrophone. Figure 11 identifies each 150-dB point calculated with this approach with the name of the associated station, and interpolates horizontally between them to bound the maximum 150-dB exposure region. The region between the origin of the graph and Station FB was extrapolated from the curve between stations FB and D4.

It is important to emphasize that the 150-dB exposure zone was typically smaller than that depicted in Figure 11, because Figure 11 was generated from maximum, not typical, received levels. Typical deep-hydrophone levels were 2–8 dB below maximum levels (Figure 10(*a*)), and riverbed levels at stations other than the spare recorder near FB were at most 8 dB, not 15 dB, greater than simultaneously-measured deep-hydrophone levels (Table 4). Also, the depicted zone was determined using data from water depths over 11 ft (3.5 m). In water depths shallower than that, the upper boundary of the zone would be closer to the riverbed because of attenuation of acoustic pressure associated with the proximity of the surface.

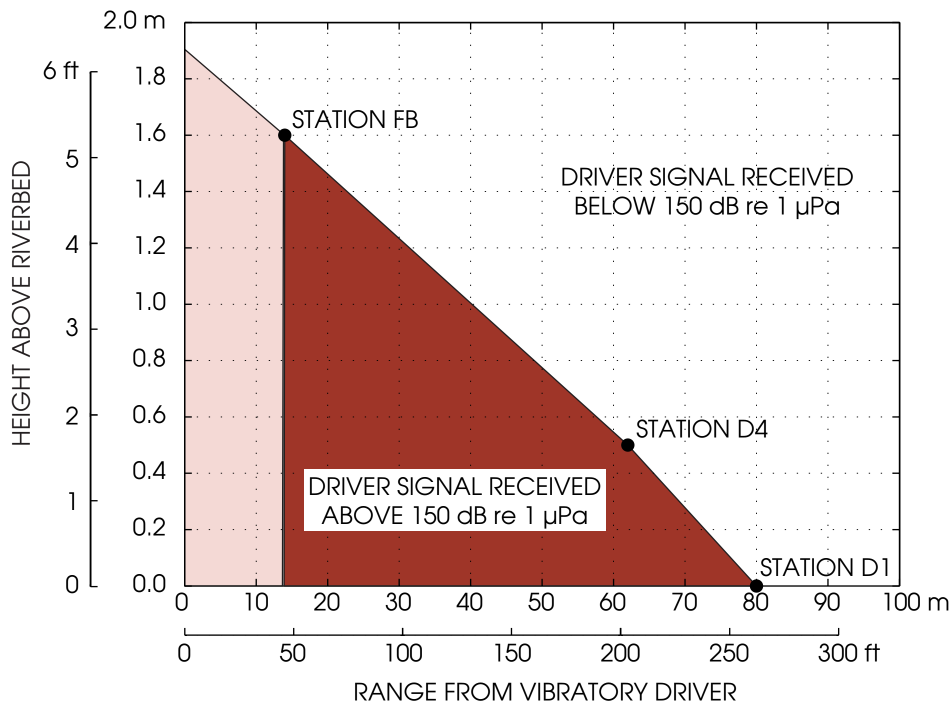

Figure 11. Estimated maximum region of SPL above 150 dB re 1 μPa. Maximum levels for the vibratory driver measured at stations FB, D1, and D4 were used to estimate the largest region potentially exposed to SPL above 150 dB re 1 μPa. The actual region exposed is unlikely to be larger than that shown here; measurements suggest that it was usually smaller. The lighter-shaded region on the left is extrapolated, as no measurements were made closer than 46 ft (14 m) to the driver.

Note that Figure 11 shows an exposure zone for sound pressure level, not for particle motion, although particle motion may be the quantity sensed by fish at these frequencies (§5.1). For acoustic waves propagating in a shallow-water waveguide, particle motion can increase with proximity to the surface even though acoustic pressure decreases, in which case Figure 11 would inaccurately predict potential impacts on fish. In the present case, however, it is doubtful that the sound field in the water was that of a propagating wave. Because the source of the strongest sound pressure appeared predominantly to be the riverbed, it is likely that particle motions as well as sound pressures decreased with distance above the bottom.

If the riverbed experienced stronger sound levels than elsewhere in the water column, fish that chose a deep or riverbed habitat would have been at greater risk of potential impact than those that chose a midwater or shallow habitat. This effect may be of concern when driving piles in estuaries or coastal areas inhabited by commercial or protected flatfish.

4.2 PARTICLE VELOCITIES AND ACCELERATIONS

The literature generally quotes sound levels in terms of acoustic pressure, because that is the easiest acoustic quantity to measure. However, because of the potential sensitivity of some fish to the particle-motion component of acoustic waves and the need quickly to convert from one form of measurement to the other, Figure 12(*a*) provides a graph that illustrates the relationship. In preparing this graph, a nominal sound speed c of 1500 m/s and water density ρ of 1000 kg/m^3 were chosen to represent brackish water in the expression velocity = pressure$/\rho c$. The figure also assumes that the signal was propagating in a free (unbounded) field; it is certain, however, that the sound field in this case was highly complex. There were undoubtedly areas where the presence of boundaries or of interference patterns led to particle motions greater or less than those indicated by Figure 12(*a*). Nevertheless it may be reasonable to calculate maximum particle velocity from maximum acoustic pressure using Figure 12(*a*), even though one would not expect maximum particle velocity to occur in precisely the same location as maximum acoustic pressure.

Some recent literature [*Mueller et al.*, 1998; *Carlson et al.*, 2001] quotes particle motion in terms of acceleration rather than velocity. Figure 12(*b*) provides a means to compare the sound pressure levels discussed in this report with particle acceleration. This graph was prepared with the same assumptions as for Figure 12(*a*), but with the additional assumption that the signal in question was a sinusoidal 16-Hz tone. This graph is not appropriate for conversion of background noise levels to particle accelerations, because the background noise was neither sinusoidal nor confined to a frequency of 16 Hz.

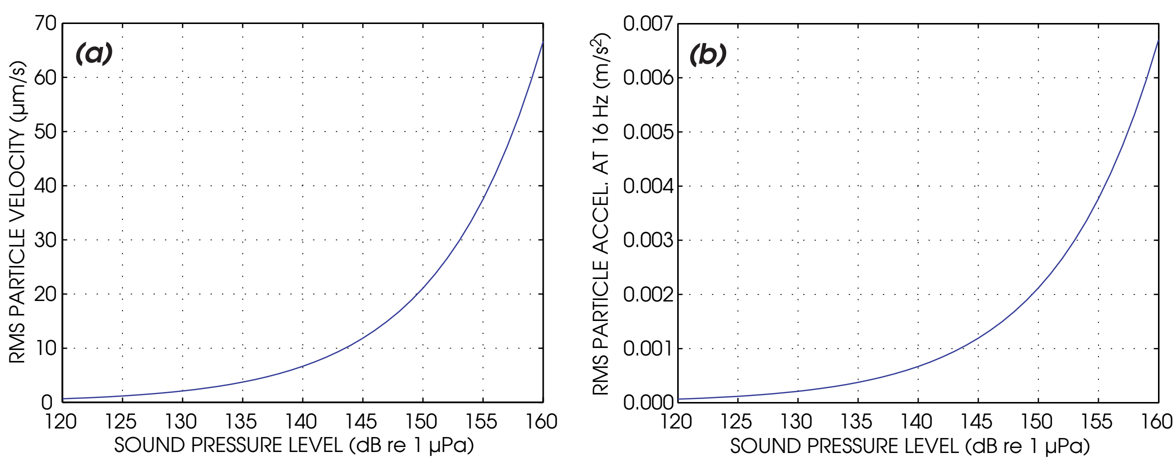

Figure 12. Particle velocity and acceleration as a function of SPL for a sinusoidal acoustic signal propagating in brackish water. The curves are for free-space propagation, and are less accurate near the source, the surface, or the bottom. To plot the acceleration curve (right) a frequency of 16 Hz was assumed. The vertical scales are presented in linear units for convenient comparison with values quoted in the literature; note that although particle motion appears to fall to zero below 120 dB re 1 μPa, it continues to be present as long as acoustic pressure exists.

5 POTENTIAL BIOLOGICAL EFFECTS

The two main species of concern in the Snohomish River at the location of pile driving are Chinook salmon (*Oncorhynchus tshawytscha*) and bull trout (*Salvelinus confluentus*). Bull trout have been listed as threatened since 1999 under the Endangered Species Act (ESA). Snohomish River bull trout belong to the Coastal-Puget Sound distinct population segment and occupy proposed critical habitat in the Puget Sound Bull Trout Management Unit. Similarly, natural spawning populations of Chinook salmon in the Puget Sound drainage were listed as threatened in 1999. The naturally spawning Chinook populations in the Snohomish River represent a significant portion of the naturally spawning Chinook salmon production in the Puget Sound region (*Schwarzen* 2004). The Snohomish River is designated Essential Fish Habitat (EFH) for Chinook, coho (*O. nerka*), and pink (*O. gorbuscha*) salmon under the Magnuson-Stevens Act. Other salmonid species that could be found in the Snohomish at the location of pile driving are chum salmon (*O. keta*), steelhead or rainbow trout (*O. mykiss*), and coastal cutthroat trout (*O. clarki clarki*). All of these species belong to the phylogenetic Order Salmoniformes, Family Salmonidae (*Robins et al.* 1991).

Almost nothing is known about the effects of sound on Chinook salmon and bull trout. However, they are closely related to the Atlantic salmon (*Salmo salar*) and the steelhead/rainbow trout for which we do have a limited amount of scientific information. This information can be used as the basis for estimating the effects of vibratory pile driving on these fish.

5.1 SENSORY BIOLOGY OF FISH HEARING

Fish have two different sensory systems to detect sound and vibration: the ear and the lateral line. These systems both rely on the same basic transducer, the mechanosensory hair cell, which is also present in higher organisms such as mammals. The two systems detect a different, but overlapping, frequency range. The fish ear detects frequencies from well below 50 Hz up to about 2,000 Hz (*Popper and Fay* 1993), but with much variation from one species to the next, while the lateral line senses frequencies from less than one up to several hundred Hz (*Coombs at al.* 1989, 1992; *Enger at al.* 1993; *Montgomery et al.* 1995). The sensitivities of the two systems differ as well. The lateral line detects signals that originate very close to the fish, on the order of a few body lengths away, whereas the ear can detect signals at considerable distances (*Kalmijn* 1988, 1989). Very-low-frequency sounds have a long wavelength relative to the size of the fish. Particle motions associated with these low-frequency sounds appear to be primarily detected by the lateral line. Particle motion or hydrodynamic flow detection by the lateral line assist fish in maintaining their position in a school, avoiding predators and finding prey.

The two inner ears of fish include three semicircular canals along with three fluid-filled sacs containing a sensory epithelium and a small calcium carbonate bony structure called an otolith. The sensory epithelium has numerous hair cells that release a neurochemical signal when the hair cells are bent. The otolith is about a third denser than the adjacent tissues and therefore moves differently than the adjacent tissues when the fish is exposed to a sound field.

This differential movement results in displacement of the sensory hairs. Excessive otolith movement may damage or shear off the sensory hairs.

Based on the orientation pattern of the hair cells mentioned above, as well as on the type of acoustic coupling between the ear and swim bladder or other gas-filled cavities, fish are broadly classified into hearing "specialists" and hearing "generalists." Specialists detect sound over a broader range of frequencies and have a much lower threshold of hearing. Goldfish (*Carassius auratus*) and clupeids such as smelt and herring are considered hearing specialists. Hearing generalists have in general less sensitive ears (*Popper and Carlson* 1998), and include the salmonids. For example, the Atlantic salmon can detect frequencies well below 50 Hz (*Knudsen et al.* 1992, 1994; *Enger et al.* 1993), but overall the sensitivity of its octavolateralis system (i.e. its ear and lateral line) is considered poor. Based on its audiogram the Atlantic salmon is functionally deaf above 380 Hz (*Hawkins and Johnstone* 1978 and see below). In addition to having higher threshold levels and a narrower hearing range, hearing generalists also seem to be less sensitive to noise exposure. *Scholik and Yan* (2002*a*) exposed individuals belonging to both categories (the fathead minnow *Pimephales promelas*, a hearing specialist, and the bluegill *Lepomis macrochirus*, a hearing generalist) to white noise for 24 h and only found a significant elevation of audiogram threshold levels in the specialist.

5.1.1 Salmonid hearing

Salmonids are considered hearing generalists in that they do not have specialized anatomical features for detecting sound and they are not particularly sensitive to underwater sound (*Popper* 2003).

A species' hearing sensitivity is generally illustrated with an audiogram, which shows hearing thresholds (the lowest sound level that can be detected in 50% of a set of trials) for a range of frequencies. Figure 13 shows a behavioral audiogram for five species of teleost (bony) fish, as reported by *Popper and Carlson* (1998). Peak sensitivity (lowest threshold) for the Atlantic salmon was 95 dB at 150 Hz; from there threshold levels increased for both higher and lower frequencies, to 107 dB at 32 Hz and 132 dB at ∼360 Hz. The threshold level at 16 Hz is therefore (by extrapolation) most likely at or above 115 dB re 1 μPa. In addition, a sound level has to be at least 10 dB above background noise for a fish to be able to detect it (*Tavolga* 1967, 1974; *Buerkle* 1968), even though specific studies on salmonids have not been done for this particular measurement. Salmonids thus appear to be most sensitive to low frequency sound around 150 Hz with a threshold of about 90–95 dB re 1 μPa (*Knudsen et al.* 1994, *Knudsen et al.* 1997, *Abbott* 1973, *Hawkins and Johnstone* 1978). Tests on Atlantic salmon indicate that they exhibit an avoidance response to infrasound at 10 Hz when they are approximately 2–3 meters from the source (*Knudsen et al.* 1997).

Hearing specialists possess a physical connection (the Weberian apparatus) between the swim bladder and the inner ear, with the swim bladder acting as an amplifier and a transformer, transforming the sound pressure component of sound into the particle velocity component of sound that the inner ear is sensitive to. Since salmonids lack this physical connection they may be more sensitive to particle motion (*Feist et al.* 1992, *Hawkins and*

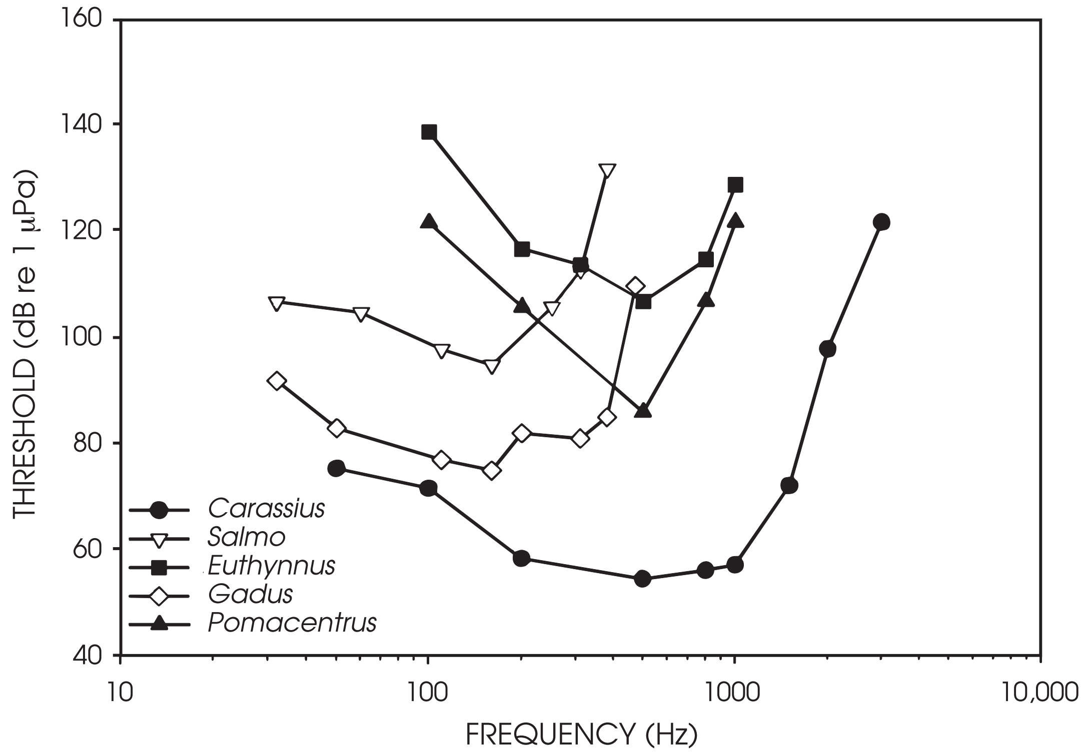

Figure 13. Auditory thresholds of several teleost fish species. All thresholds were determined via behavioral methods in which fish were trained to perform some task whenever they heard a sound. *Carassius auratus* (goldfish) is a hearing specialist (*Jacobs and Tavolga*, 1967) and can detect sounds up to about 3,000 Hz. *Salmo salar* (Atlantic salmon) (*Hawkins and Johnstone*, 1978), *Gadus morhua* (Atlantic cod) (*Chapman and Hawkins*, 1973), *Pomacentrus leucostictus* (beaugregory) (*Myrberg and Spires*, 1980), and *Euthynnus affinis* (kawakawa) (*Iversen*, 1969) are not specialists, so they hear a narrower range of frequencies and their thresholds are higher when compared to goldfish. Hearing by the kawakawa is particularly poor, and this may be explained by the species' lack of a swim bladder. Thus, unlike the other species, the kawakawa only detects signals by particle displacement. *(Figure and caption from* Popper and Carlson *(1998), used with permission.)*

MacLennan 1976). Particle motion is what causes hearing in the fish ear and at very low frequencies particle motion is detected by the lateral line. Much of future research will be focused on the role of particle motion in fish hearing and pile-driving impacts. The absence of particle-motion data associated with many of the fish hearing tests conducted in the past confounds interpretation and comparison of many of the published reports.

Fishes with swim bladders, such as the salmonids, are sensitive to underwater impulsive sounds because of swim bladder resonance, which is thought to occur in the frequency band of most sensitive hearing (200–800 Hz, *Caltrans* 2002). When subjected to intense impulsive sounds, swim bladder resonance can lead to severe injuries.

5.2 POTENTIAL EFFECTS OF VIBRATORY PILE DRIVING

5.2.1 Prior studies of vibratory pile driving

Pile driving with large impact hammers is known to result in fish mortalities (*Caltrans* 2001, *Caltrans* 2003, *Longmuir and Lively* 2001, *Vagle* 2003). However, none of the above reports address vibratory drivers. There are two grey literature reports assessing the effects of vibratory drivers on fish (*Nedwell et al.* 2003, *Dolat* 1997). Neither report has been peer-reviewed or published in a refereed scientific journal, but they are the only references known to the authors that relate to fisheries impact assessment from vibratory drivers such as were used in the Snohomish River project.

Nedwell et al. (2003) used 10-in (25.4-cm) brown trout (*Salmo trutta*) placed in cages at various distance from the pile including one cage as close as 50 m from the pile. The cages were hung 8 ft (2.5 m) below the surface. No data are provided on the frequency of the hydroacoustic signal produced by the vibratory driver. The calibration data for the hydrophones suggest that none of the hydrophones were calibrated for frequencies below 4 kHz. The low-frequency capabilities for the signal processing equipment are not provided. Data on the drivers are not provided. These deficiencies leave some question as to the adequacy of their sound pressure measurements at frequencies below 1,000 Hz where most of the vibratory energy was probably located. They reported no detectable underwater noise from the vibratory driver at a distance of 1368 ft (417 m). Monitoring with video cameras indicated there was no startle response or increase in fish activity during vibratory-driver operations.

Dolat (1997) measured underwater SPL from construction activities during the Baldwin Bridge demolition project in Connecticut. Machinery recorded included a hoe ram used to drive H-piles, and vibratory drivers during driving of sheet piles. The monitoring vessel was positioned at different distances and underwater sounds were recorded at different depths. The maximum SPL from vibratory drivers driving sheet piles was 156 dB re 1 μPa at 20 Hz measured at a range of 110 ft (33.5 m). No impacts on fish were noted.

5.2.2 Near-term and delayed mortality

Divers present in the Snohomish River before, during, and after pile-driving operations reported no dead fish, although many live salmonids and other fish were seen before driving began. Observers on the surface saw no indications of immediate or near-term fish mortality such as moribund fish floating to the surface or increased activity by gulls. There may have been delayed mortalities, but debilitated fish are likely to be subjected to excess predatory pressure and never noted unless they were to be held in a cage for at least 4 days.

5.2.3 Permanent hearing loss

A number of studies have examined the damage to the inner ear of fishes exposed to intense sounds for varying amounts of time. Barotraumas are pathologies associated with exposure to drastic changes in pressure, such as occur during explosions with short rise times and high peak levels on the order of 230 dB re 1 µPa [*Norris and Møhl*, 1983]. This category of injuries will not be examined further since the vibratory driving sounds we are dealing with are not impulsive in nature. Continuous sounds can also lead to ear injuries in fish. For example, *Enger* [1981] found destruction of auditory hair cells in the saccule (an organ of the inner ear) of cod (*Gadus morhua*) exposed to continuous tones for 1–5 hours, at frequencies of 50–400 Hz and SPL of 180 dB re 1 µPa. Similarly, exposing goldfish (*Carassius auratus*) for about two hours to an SPL of 189–204 dB re 1 µPa at frequencies of 250 and 500 Hz resulted in the destruction of auditory sensory cells. The destruction of ciliary bundles was found to correlate with SPL at a 95% confidence level [*Hastings et al.* 1996]. Oscars (*Astronotus ocellatus*) exposed to 180 dB re 1 µPa at 300 Hz for one hour suffered the destruction of sensory cells, whereas they did not when the testing frequency was 60 Hz [*Hastings et al.* 1996]. Damage to hearing tissues from intense sound may not be visually evident in tissues immediately after exposure [*Popper and Carlson*, 1998].

In most of these studies, the levels that led to damage of the ear were 60 to over 100 dB above threshold levels, as determined behaviorally [*Fay*, 1988]. The level above threshold could offer an index of potential damage from a high intensity sound [*Popper and Carlson*, 1998]. If so, a high intensity sound that might not affect hearing generalists such as the oscar and salmonids might damage hearing specialists with a lower threshold. In the present effort, sound pressure levels for the one-third octave band centered at 16 Hz were at most 40–50 dB above threshold levels and would therefore not be expected to cause ear damage.

The degree to which observations on one species belonging to a systematic group (i.e. Atlantic salmon as part of the salmonid family) can be extrapolated to other species belonging to the same systematic group is not known, nor is the degree to which the sensitivity, extent of ear damage and amount of possible regeneration varies with the fish's developmental stage [*Popper and Carlson*, 1998].

5.2.4 Temporary hearing loss

The fathead minnow (*Pimephales promelas*), a hearing specialist, exhibited temporary hearing threshold shift (TTS) after 24 hr of white noise exposure at 142 dB (*Scholik and Yan* 2001). The same exposure to bluegill (*Lepomis macrochirus*), a hearing generalist, did not result in TTS (*Scholik and Yan* 2002*b*). Salmonids are hearing generalists and would probably not experience TTS if exposed to sound pressures of 142 dB. However, the exposure level at the pile-driving site in this effort was higher than 142 dB and it is possible that salmonids may have experienced an increased threshold of hearing. On the other hand, considering that salmonids routinely migrate up and down parts of rivers where there is considerable gravel movement and underwater noise associated with waterfalls, it seems likely that SPL as high as the highest level measured in this effort, 161 dB, would not result in a permanent threshold shift (PTS) even if a brief TTS did occur.

5.2.5 Audibility and avoidance

Early attempts to control the behavior of migrating salmonids with sound revealed that these fish rarely react detectably to intense sounds. *Burner and Moore* [1962] used frequencies of 67–70 Hz at SPL of up to 182 dB re 1 µPa and were not able to elicit responses from the salmonids. *Knudsen et al.* [1992, 1994] found that the most marked behavioral responses of Atlantic salmon to sound were at low frequencies (5–10 Hz), but the fish had to be very close to the sound source (within 2 m).

More recently, *Mueller et al.* [1998] showed that sound frequencies of 8–12 Hz provoke an innate avoidance response in wild and hatchery Pacific salmon and steelhead in the age range from swim-up fry to smolt. The authors used acoustic particle accelerations greater than 0.01 m/s^2 to induce avoidance; the background ambient acceleration in their test tank was 0.0069 m/s^2. Figure 12(*b*) shows that this background-noise acceleration value is about the same as that associated with the strongest sound pressure levels measured in the present effort.

At the closest measurement station (FB), typical received levels in the 16-Hz one-third octave band varied between 145 and 155 dB re 1 µPa (Figure 10(*a*)). This range lies well above the 115 dB threshold level estimated for Atlantic salmon at $\sim$16 Hz. If we assume that the Atlantic salmon is a representative member of the salmonid family, a salmonid near Station FB would most likely hear the sounds produced by the vibratory driver. At more distant stations, on the other hand, mean received levels in the driver's one-third octave band (Figure 10(*a*)) were close to or below the Atlantic salmon's hearing threshold and may not have been more than faintly audible to salmonids in general.

Generations of anadromous salmon and bull trout using the Snohomish watershed pass through the waterways of Puget Sound, parts of which are heavily industrialized. In another industrialized waterway, San Francisco Bay, background noise levels are on the order of 140–155 dB as recently measured on the San Francisco Bay Bridge project and at the port of Oakland. Similar background noise levels are reported by *Nedwell et al.* (2003). In a sense, fish voluntarily enter such sound environments; or it can be said that these sound environments are not an impediment to normal migratory behavior. *Nedwell et al.* (2003) propose that the threshold for avoidance behavior is 90 dB above the threshold of hearing at the most sensitive frequency. For salmonids, using the Atlantic salmon audiogram shown in Figure 13, that would be about 180 dB, well above the levels measured in this effort.

6 CONCLUSIONS

Sound levels associated with industrial activity are usually characterized as uniformly decreasing with horizontal range. Maps of regions exposed to sound levels above a regulatory threshold, for example 150 dB re 1 µPa, may often depict their boundaries as a simple circle centered at the source. In this effort, however, the profound depth and frequency dependence of the vibratory driver's sound field suggests that – at least for vibratory pile driving in shallow water – a sound-exposure prediction that varied only with horizontal range from the source would be inadequate. A fish located 46 ft (14 m) from the driver, for example, could have decreased its received level by 23 dB by moving from 15-ft (4.5-m) depth up to 3-ft (1-m) depth, a distance of 12 ft (3.5 m). The same fish would have had to swim approximately 200 ft (61 m) horizontally to reduce its received level by a similar amount. At the same time, a fish resting on the riverbed 548 ft (167 m) from the driver could have experienced changes in received level as great as 20 dB resulting from a 1-Hz change in the driver frequency. These findings suggest that vibratory pile driving in shallow-water environments may expose demersal fish, such as flatfish, to higher sound levels than would in general be experienced by midwater fish such as salmonids.

The sound pressure levels measured in this effort fell far short of those discussed in the literature as resulting in fish mortality, injury, permanent hearing loss or other physiological stress. The vibratory driver did produce particle motions that were probably perceptible to the salmonid lateral line, resulting in some degree of avoidance behavior for salmonids that were both close to the pile and deep within the water column. It is problematic to consider such short-term avoidance behavior an adverse impact; this same behavior is executed numerous times each day by fish avoiding objects and predators while navigating along the river banks guided by differential flow patterns.

Vibratory-driver sounds were present in the river for only 39 minutes total on 11 November 2004. The longest uninterrupted period of driving lasted 8 minutes. Compared with the incidence and duration of other more common sources of elevated sound, such as heavy river flow and vessel activity, the vibratory driver's total acoustic contribution appears relatively small.

The potential biological consequences of the vibratory driving in the Snohomish River are difficult to quantify due to the complexity of the acoustic field surrounding the driver and the limits of current knowledge regarding fish response to sound. However, given (1) the brief and temporary nature of the driving; (2) the relative weakness of received levels compared with those thought to cause injury or significant response; (3) the commonality of other strong natural and anthropogenic sounds in the river as well as elsewhere in the salmonid migration path; and (4) the availability of shallow depths as an easy escape route from higher sound levels, we do not expect any significant long-term impact to salmonids associated with this vibratory-driving project.

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