ACOUSTIC MONITORING OF BARRIER WALL INSTALLATION AT THE FORMER RHÔNE-POULENC SITE, TUKWILA, WASHINGTON

Prepared for:

RCI Environmental, Inc.
P.O. Box 1668, Sumner, WA 98390

Greeneridge Report 290-1
Revised 6 March 2003

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1 SUMMARY

A series of underwater acoustic measurements took place in early 2003 to assess the potential impact of vibratory beam driving on salmonid fish in the Duwamish River, near Seattle, Washington. The measurements were made adjacent to the former Rhône-Poulenc industrial site during remediation for the presence of harmful materials. To prevent the escape of these contaminants, the remediation effort used a vibrating beam to inject a vertical barrier wall of self-hardening slurry into the ground surrounding the site. Sounds reaching the river via ground conduction from the vibrating beam were measured under "worst-case" conditions, that is, conditions under which the strongest sounds would be expected in the water, and compared with typical ambient sounds recorded before driving began.

A tonal sound with a frequency between 26 and 28 Hz was found to couple from the vibrating beam into the river. The strongest sound pressure level measured for this tone, averaged over a 1-s interval, was 155 dB re 1 μPa at a range of 187 ft (57 m) from the vibrating beam. Levels measured at a distance of 761 ft (232 m) were in the range 86–121 dB re 1 μPa, comparable to the levels of ambient noise measured in the same area at a time when the driver was not operating.

Comparison of these received levels with those known to affect salmonid fish indicated that salmonids located in the Duwamish River adjacent to the site would very likely hear the vibratory-beam sounds, at least under the worst-case conditions of this experiment. Equally clear was that even the strongest vibratory sounds measured would not result in immediate physical injury to exposed salmonids. The likelihood of behavioral reaction, potentially leading to increased stress or predation, remained less certain. Available literature indicated that sound pressure levels greater than the maximum recorded in this study would be required to induce behavioral reactions by salmonids.

2 INTRODUCTION

In January 2003, Slurry Systems, Inc., began installing a self-hardening slurry barrier wall around an industrial site located seven miles south of downtown Seattle. The site, once used by Rhône-Poulenc, Inc. and now owned by Container Properties, LLC, contains toxic materials such as arsenic, copper, mercury, and toluene. The barrier installation is part of a remediation program to minimize leaching of these materials into the adjacent Duwamish River and other neighboring areas.

While the benefits of successful remediation are clear, concern has arisen that the slurry injection itself may pose an acoustic hazard to protected fish in the Duwamish. To inject the slurry barrier, the operators must drive a beam, vibrated at a frequency in the tens of hertz, into the ground to depths up to 80 feet. The slurry is pumped through hollow ducts in the beam to injection holes in its leading edge (Figure 1), where it enters the void created as the beam is withdrawn. A crane with dedicated machinery (Figure 2) supports, drives, and vibrates the beam while maintaining slurry flow. Sound from this equipment, especially from the vibrating beam, may couple efficiently through the ground and into the Duwamish.

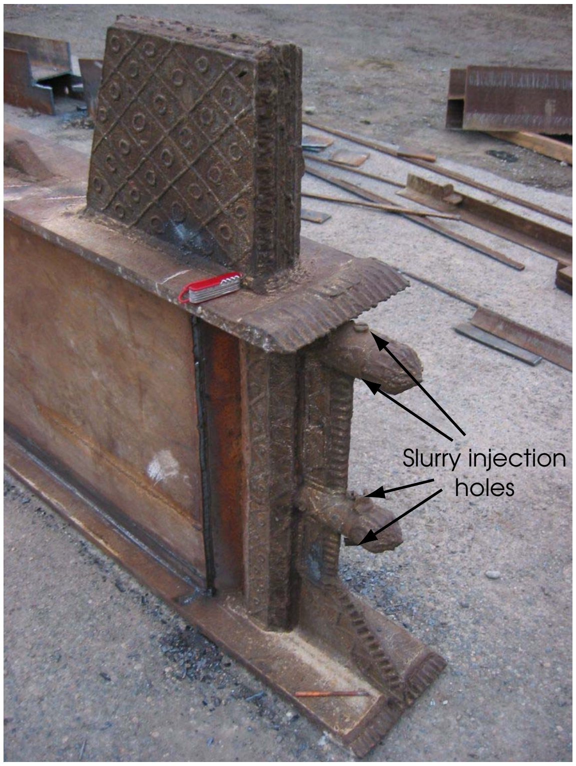

Figure 1. Leading edge of the vibratory beam. The slurry exit holes are visible in the sides of the two cylindrical protrusions.

Figure 2. Supporting crane, pump, and vibration machinery.

The primary environmental contractor, URS Corporation, concluded that sounds introduced into the Duwamish River by the vibratory driver should be measured and their potential impact on protected fish assessed. The following factors contributed to this conclusion:

1. The uncertainty regarding subsurface noise radiated from the vibratory beam;
2. The high usage of this portion of the Duwamish by juvenile and adult salmonids;
3. The length and depth of the barrier wall along the shoreline;
4. The duration of time it would take to construct the barrier; and
5. The possibility of needing to work outside the regulatory in-water work window.

As a result of this assessment, Greeneridge Sciences was contracted to measure and compare ambient and vibratory-beam sound levels in the Duwamish River in the vicinity of the former Rhône-Poulenc site. This report describes this effort and its results.

2.1 REVIEW OF UNDERWATER ACOUSTIC CONCEPTS AND TERMINOLOGY

The conclusions of this study 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 combined phenomena of ***pressure*** and ***particle motion*** comprise the acoustic wave. The SI (metric) measure of pressure amplitude is the pascal (Pa), approximately equivalent to 0.000145 pounds per square inch. Particle motion is described in terms of particle velocity, whose SI measure is meters per second.

The word ***level*** denotes a sound measurement in ***decibels***. A decibel (dB) is defined as ten times the base-ten logarithm of the ratio between a squared test amplitude (pressure or particle velocity) and a corresponding squared reference amplitude. When the amplitudes describe the pressure of acoustic waves, the squared amplitudes vary in direct proportion to the power transmitted by those waves. Thus the decibel measures the difference, in orders of magnitude ($\times 10$), between a test power and a reference power: 10 dB means ten times the power, 20 dB means one hundred times the power, 30 dB means one thousand times the power, and so on. Because the decibel is always a relative measure, any absolute value expressed in decibels is meaningless without an accompanying reference. In describing underwater sound pressure, the reference amplitude is usually 1 micro-pascal (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.

Data-gathering instruments typically measure acoustic-pressure amplitude or particle-velocity amplitude. Because decibels are defined in terms of *squared* amplitudes, the relationship between a signal's amplitude in micropascals and its level in dB sometimes causes confusion. For example, increasing a signal's level by 20 dB, or one hundred times the power, requires only a tenfold increase in amplitude. An increase of 10 dB, or ten times the power, is only about three times the amplitude. Doubling the power of a signal raises its level by 3 dB, while doubling the amplitude of a signal raises its level by 6 dB.

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 the sound loudness. For example, a human would perceive a level of 90 dB to be twice as loud as a level of 80 dB. As noted earlier, this 10 dB increase in level is (in physical terms) a tripling of the pressure, but it is perceived by humans as a doubling in loudness.

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 1011 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)***. An 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 SPL. Since the results are the same, the terms "SPL" and "rms pressure level" are used interchangeably.

Acoustic measures such as SPL provide physical information about sound signals, but they do not in themselves signify the impact of sound on humans or other life. The physiology and psychology of the listener is as important to the issue of impact as the physical properties of the sound received. Significant misinterpretations can occur if one assumes that other species hear sounds that humans can hear, or that sounds inaudible to us are also inaudible to them.

Measured sound levels depend on the frequency range, or bandwidth, under consideration. If a sound involves frequencies outside the analysis bandwidth, those portions of the sound will not be included in the analysis. In this case, as the analysis bandwidth increases, computed in-band SPL levels will also increase. To avoid this dependence, SPL values are often computed and plotted on a per-unit frequency basis (per hertz). Such levels are called ***spectrum levels*** or ***spectral density levels***, and carry units of dB re 1 $\mu\text{Pa}^2/\text{Hz}$. Graphs of spectral density vs. frequency present much of the amplitude and frequency information available about an acoustic signal, but are sometimes difficult to interpret for time-varying signals such as seismic pulses.

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. For example, the 1/3-octave band centered at 100 Hz extends from 89 to 112 Hz, whereas the band centered at 1000 Hz extends from about 890 to 1120 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)] results in the 1/3-octave band level. Sound levels are often presented for 1/3-octave bands because the effective filter bandwidth of mammalian hearing systems is roughly proportional to frequency and often about 1/3 octave. That is, a mammal's perception of a signal at a given frequency will be strongly affected by other sounds within a 1/3-octave band around that frequency. For frequencies above 5 Hz, the 1/3-octave band level of any broadband sound exceeds the spectrum level because the 1/3-octave bandwidth exceeds 1 Hz. Likewise, the overall level (considering all frequencies) of a broadband sound exceeds the level in any single 1/3-octave band.

3 METHODS

Field recordings took place on 10, 11, and 31 January and on 1 February 2003. On 10 and 11 January over an hour of acoustic recordings were made of ambient sounds, both in the vicinity of the former Rhône-Poulenc site and at locations further downriver. Monitoring of vibratory-beam sounds began on 31 January and completed on 1 February 2003.

3.1 DATA ACQUISITION

Acoustic recordings took place in several locations (Table 1), both before and during slurry-wall installation. Figure 3 shows the recording locations and the site of the vibratory beam. The photographs in Figure 4 provide additional reference for the locations and landmarks. The ambient-recording locations were chosen to assess typical background sounds at both minimum and maximum river flow. The three recording locations used to measure the vibratory beam—Station 1, Station 2, and Station 3—were selected to determine the range of sound levels that fish might experience as they pass the site during barrier-wall installation.

Water depths near the former Rhône-Poulenc site fluctuate with the tide by as much as 13 ft (4 m). Shallow water depths attenuate sound transmission at low frequencies, so to estimate the strongest received levels, recordings of the vibratory driver were made within 4 ft (1.2 m) of the highest tide level. Recordings of ambient sounds were also made within 4 ft of high water, with the exception of the measurements at full tidal flow and at the First Avenue bridge, which were made at 5 and 6 feet (1.5 m and 1.8 m) below high water respectively. A chartered 34-foot trawler, the *Turnagain* (Figure 5), provided the recording platform.

At each recording site, a “string” of four hydrophones lowered into the river obtained acoustic data. The string included anti-strum feathering to prevent oscillation of the hydrophone cables. The hydrophones were arranged at three positions on the string at 6.6-ft (2-m) intervals, with the deepest hydrophones intended to be located at 16.4 ft (5 m); in shallower recording locations it was necessary to deploy less of the string, to avoid impacting the riverbed with the lowest hydrophones. Table 2 lists the hydrophones and all hydrophone

TABLE 1. Recording locations.

Location	Water Depth ft (m)	Description
Station 1	17 (5.2)	Anchored near southwest corner of site
Station 2	16 (4.9)	Tied up at Delta Marine Industries dock
Station 3	27 (8.2)	Tied up at end of Slip 6
Slip 6	27 (8.2)	Tied up at end of Slip 6
Barge	22 (6.7)	Tied to barge in middle of river
Tidal Flat	12 (3.7)	Drifting over intertidal zone adjacent to site
Yacht Slip	22 (6.7)	Tied up in slip, Duwamish Yacht Harbor
Full Tidal Flow	29 (8.8)	Drifting in midstream at approximately 1 knot
1st Avenue Bridge	34 (10.4)	Drifting under highway bridge

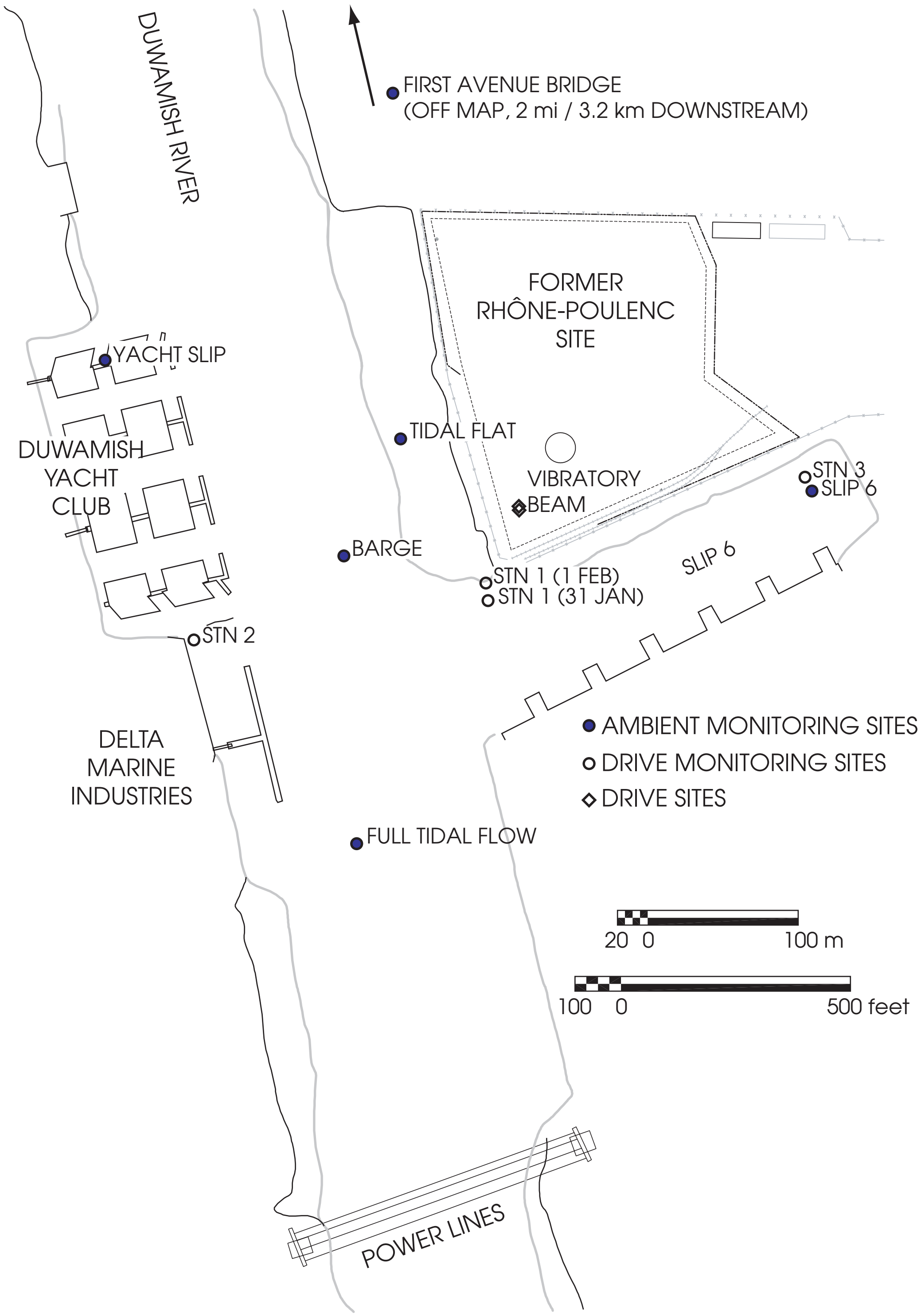

Figure 3. Map showing recording and vibratory beam locations. Stations 1, 2, and 3 (STN 1, STN 2, STN 3) mark locations at which vibratory driving was monitored. All other monitoring sites were used to record ambient sound activity.

(a) Duwamish River, looking due south

(b) Duwamish River and former Rhône-Poulenc site, looking due north

(c) Slip 6, looking due east

Figure 4. Three views of the former Rhône-Poulenc site.

Figure 5. *Turnagain*, the 34-foot trawler used for all recordings. The crane and guide for the vibratory beam, being assembled and tested near the northwest corner of the site, are at left.

TABLE 2. Hydrophones.

Hydrophone	Nominal sensitivity dB re 1 V/μPa	Depth ft (m)	Alternate depth[a] ft (m)	Alternate depth[b] ft (m)
ITC 1042	-204.0	3.3 (1.0)	2.3 (0.7)	—
ITC 1103	-196.4	9.8 (3.0)	8.8 (2.7)	3.3 (1.0)
ITC 1032	-194.0	16.4 (5.0)	15.4 (4.7)	9.8 (3.0)
ITC 6050C	-159.0	16.4 (5.0)	15.4 (4.7)	9.8 (3.0)

[a] Hydrophone depths for Station 1 on 31 January.

[b] Hydrophone depths for Tidal Flats, Station 1 on 1 February, and Station 2.

depths used. Unless otherwise specified, all data discussed were obtained with the 6050C hydrophone, one of the pair of hydrophones positioned at the bottom of the string. This hydrophone is designed to measure relatively weak signals, and provided the best signal-to-noise ratio of the four hydrophones used.

Signals from the hydrophones were conditioned by custom amplifiers and recorded with a 24 kHz sampling rate on data-quality digital audio tape (DAT) by a Sony PC208Ax instrumentation recorder. Sound levels were constantly monitored during recordings to obtain the highest-quality data. When sound levels appeared too low or too high, adjustments to gain and record levels restored useful signal-to-noise ratios or avoided saturation.

During recordings, the *Turnagain* shut down her engines, pumps, generator, refrigerator, depth sounder, and any other gear that could contaminate the acoustic data. Crew avoided noisy movements or activities. At three of the recording locations—“Tidal Flat,” “Full Tidal Flow,” and under the First Avenue Bridge—acoustic recordings were made while *Turnagain* drifted, either for convenience or to minimize noise artifacts from water flow past the hydrophones. All other recordings were made with the *Turnagain* secured in position.

Positions were determined using Garmin GPS 12MAP (10 and 11 January) and GPS 12CX (31 January and 1 February) handheld GPS receivers. Ranges to the vibratory beam were obtained from a Bushnell “Yardage Pro Compact 800” laser rangefinder (for Station 1) or by calculation given the GPS positions of the vessel and the vibratory driver (Stations 2 and 3). Table 3 shows ranges to the vibratory driver for each driver recording site. Water depths were obtained with the sounder located on board the *Turnagain*, and are corrected for the sounder depth, but not for the tide; water depths given throughout indicate the depth at the time measurements were taken, not the mean-lower-low-water value printed in navigational charts.

Once acquired, the acoustic data were transferred digitally to desktop computers running custom analysis software. The data were calibrated for the specific hydrophones used and processed to determine broadband (4–10,000 Hz) and one-third octave band sound pressure levels (SPL). 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 the SPL in a one-third octave band for that segment. The analysis segments overlapped by a factor of 10, that is, each new segment was shifted in time by 0.1 s from the previous segment. This process produced a time series, effectively sampled at 10 Hz, representing the fluctuation of SPL within the selected one-third octave band.

TABLE 3. Recording ranges.

Location	Range to Beam ft (m)
Station 1 (31 Jan)	210 (64)
Station 1 (1 Feb)	187 (57)
Station 2	761 (232)
Station 3	627 (191)

3.2 OPERATION OF VIBRATORY DRIVER

Slurry Systems, Inc., operated the vibratory driver specifically for these tests as part of a planned experiment. The flexibility afforded by a dedicated source allowed investigation of "worst-case" sound pressure levels, that is, the strongest received levels likely to occur. The following steps maximized the sound levels recorded for this study:

1. The driver was operated at the southwest corner of the site, where maximum sound transmission into the Duwamish would be expected.
2. The driver was operated at maximum power. In normal operation weaker vibration settings may be used.
3. For recordings at Station 1 and Station 2, the drive operators started an entirely new hole. In normal operation, each insertion of the beam typically overlaps the previous hole by 30%. Slurry Systems operators report that, because of this overlap, subsequent insertions of the beam produce audibly less sound than the primary insertion. Starting entirely new holes ensured that maximum sound levels would be produced.

During operation of the vibratory driver, an RCI observer on site reported beam depth in 5-ft intervals to the *Turnagain* crew.

4 RESULTS AND DISCUSSION

Initial analysis focused on characterization of the vibratory-driver source frequency. Animals' ability to detect a sound signal in the presence of background noise typically depends on the strength of the signal compared against the noise level in a band of nearby frequencies, and less so against the broadband or overall noise level. Because of this, sound sensitivity and exposure are often quantified in terms of one-third octave bands (see §2.1 for a review of this and other acoustical terminology). Before levels received from the vibratory driver could be compared meaningfully with the background noise levels, it was critical to determine which one-third octave band the source would affect.

Data from Stations 1, 2, and 3 showed the vibratory-beam signal to be nearly sinusoidal, and to vary in a narrow range of frequencies between 26 and 28 Hz. These frequencies are part of the 25-Hz one-third octave band that extends from 22.4 to 28.2 Hz. Therefore the 25-Hz one-third octave band was chosen to analyze background noise levels for comparison with levels received from the vibratory driver.

4.1 AMBIENT SOUNDS

The Duwamish, in the vicinity of the former Rhône-Poulenc site, is a noisy river. Anthropogenic sounds were easily detectable in all analyzed data. These sounds originated from vehicle traffic, aircraft, machinery, and, occasionally, vessel traffic. Table 4 lists the dominant sounds observed at each of the ambient-recording locations.

A variety of mechanical sounds from unknown sources dominated the ambient recordings. The sounds were qualitatively characteristic of engines, motors, and pumps. Frequent aircraft sounds punctuated the recordings, unsurprisingly, as runways of the Seattle-Tacoma International Airport come as close as 3.5 mi (5.6 km) to the south of the site, and the runway at Boeing Field lies only 0.5 mi (0.8 km) to the northeast. Under the First Avenue Bridge, 2.0 mi (3.2 km) downstream to the northwest, constant vehicle traffic over a metal-grate road surface (Figure 6) was found to couple sound into the river. Vessel propulsion sounds, however, a dominant component in the background noise of other waterways, were nearly absent in this part of the Duwamish. The former Rhône-Poulenc site lies near the end of the navigable portion of the river; the few vessels observed underway were associated with Delta Marine Industries, the Duwamish Yacht Club, or the Slip 6 barge dock.

TABLE 4. Ambient sound characteristics.

Location	Sounds
Slip 6	Machinery, aircraft overflights
Barge	Machinery, aircraft overflights
Tidal Flat	Machinery
Yacht Slip	Unidentified infrasonic rumble (10 Hz and below)
Full Tidal Flow	Infrasonic rumble, machinery, sounder (not *Turnagain*'s)
1st Avenue Bridge	Traffic noise coupling through bridge pylons

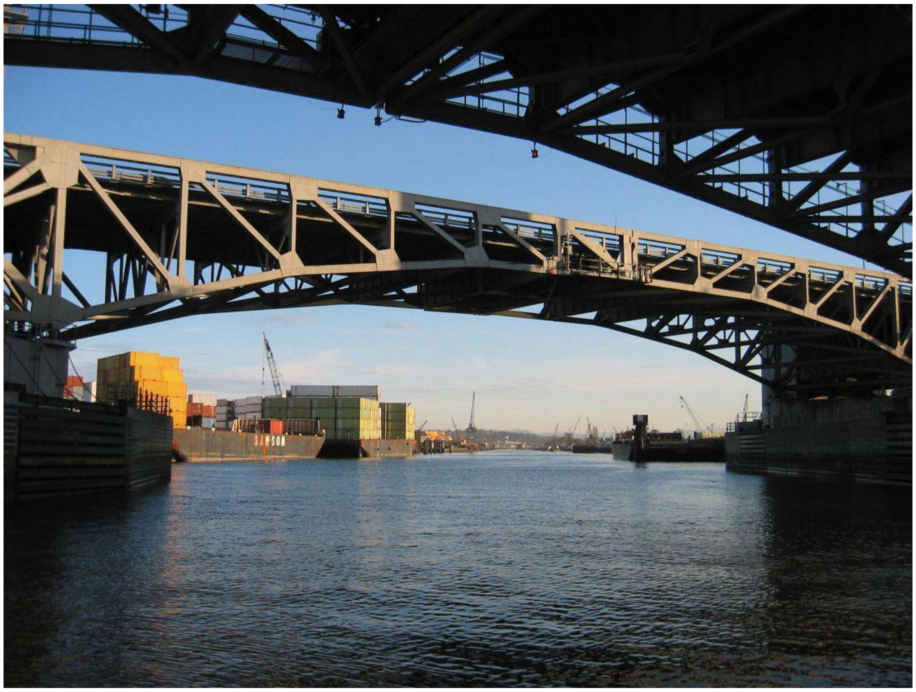

Figure 6. The First Avenue Bridge.

Figure 7(a) shows sound pressure levels (SPL) received at the ambient-recording locations, both as broadband levels and as levels in the 25-Hz one-third octave band. The levels were determined by averaging from 20 s to 5 min of data (longer averaging times were chosen for records that exhibited more variability). This means that the values shown do not represent the received level of any individual transient sound, but rather an average background. Since aircraft overflights were common, however, one exception was made: an aircraft recording made at the "Barge" site was selected for its strong signal-to-noise ratio and analyzed only over its audible duration. The resulting bar in Figure 7(a) represents the SPL during this transient sound, not a constant background level due to aircraft.

As depicted in Figure 7(a), the ambient broadband (4–10,000 Hz) SPL varied from 110 to 130 dB re 1 μPa, while the corresponding SPL in the 25-Hz one-third octave band varied from 100 to 116 dB re 1 μPa. In the 25-Hz band, these values straddle the 106-dB upper limit of "prevailing noise"—i.e., natural and anthropogenic noise excluding rare events such as earthquakes and explosions—documented by *Wenz* [1962] for the ocean. This comparison indicates that background sound levels measured in the Duwamish were comparable to or exceeded the strongest daily levels one might typically expect in the ocean. Note, however, that the anthropogenic sounds encountered may have diminished at night. No recordings were conducted at night as part of this experiment.

While relatively strong background levels were expected due to the industrial character of the area, the relative strength of ambient levels at the "Tidal Flat," "Yacht Slip," and "Full Tidal Flow" stations was surprising. Further inspection and playback of these records showed

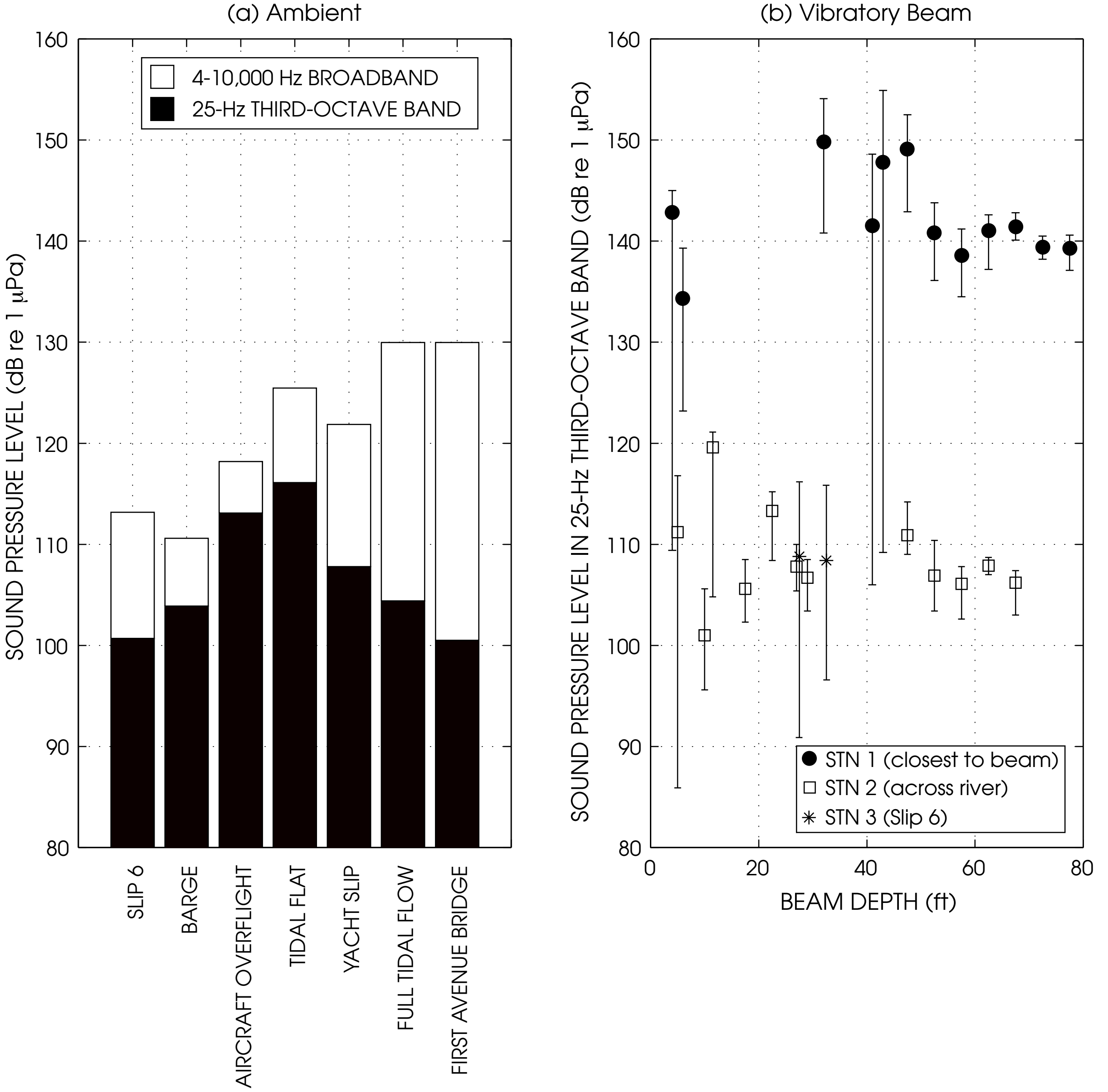

Figure 7. Ambient (a) and vibratory-driver-produced (b) sound pressure levels. For (b), the maximum and minimum received levels observed above and below the mean for a given beam depth are represented as vertical bars on the plot symbol.

the “Tidal Flat” recording to contain machinery sounds dissimilar from those in the other recordings; the “Tidal Flat” measurements may have been influenced by machinery that did not operate at other times. Recordings at the “Yacht Slip” and “Full Tidal Flow” stations were found to contain a strong infrasonic (10 Hz and below) rumble. The source of this rumble could not be determined. It may have been an artifact of flow past the hydrophones, although this is unlikely as the hydrophone string was equipped with anti-strum fairing, and the maximum current observed was only 1.2 knots. The non-periodic nature of the rumble suggests it was of natural origin, possibly associated with boundary turbulence between the salt-water and fresh-water layers.

4.2 RECEIVED LEVELS FROM THE VIBRATORY DRIVER

Sound levels associated with the vibratory driver varied with time, beam depth, hydrophone depth, and propagation distance (see Table 3 for the range of the vibratory beam to each of the driver-recording stations).

4.2.1 Received levels as a function of time and beam depth

Figure 8 shows an example of the SPL time series in the 25-Hz one-third octave band obtained for Station 1, when the beam was at depths between 40 and 65 ft and at a range of 187 ft (57 m) from the hydrophones. The received levels shown in Figure 8 were far from consistent during driving activity, varying from 106 to 155 dB re 1 μPa; the latter was the strongest level received during the entire experiment. The extreme temporal variability observed in this and a few other records probably resulted from the frequent suspension of driving operations to allow adjustments to the vibratory and slurry injection equipment.

Figure 7(b) plots the temporal variability of received levels as a function of recording station and beam depth. The plot symbols indicate mean received level in the 25-Hz one-third octave band (obtained by averaging the 1-s SPL values over a range of beam depths on either side of the indicated beam depth, usually about ±5 ft), while the vertical bars indicate the range between the minimum and maximum 1-s SPL values. The figure shows that the extreme variability of received level depicted in Figure 8 occurred at a few other times as well, but that mean levels remained relatively stable within a 10-dB range for beam depths greater than 15 ft. The strongest mean levels were observed for beam depths between 10 and 50 ft. Table 5 summarizes the range of sound pressure levels received from the vibratory beam. The table also gives the highest of the mean levels presented in Figure 7(b). These “highest mean” levels may be used as representative received levels for conservative analysis.

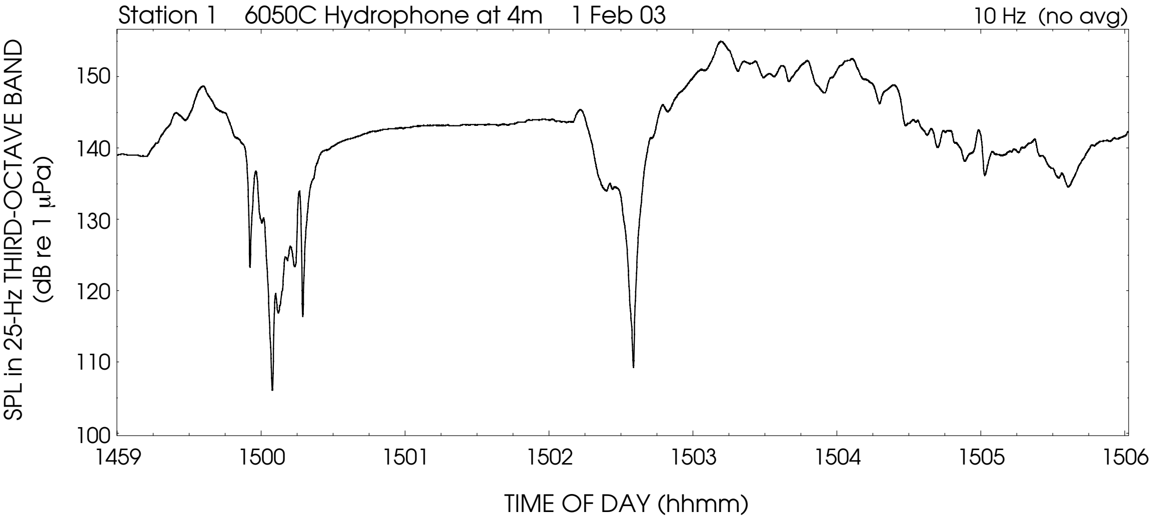

Figure 8. Fluctuations in the 25-Hz one-third octave band level at Station 1 during driving of the vibratory beam. Beam depth increased during this record from 40 ft (at 1459) to 45 ft (at 1504) and 65 ft (at 1506). The strongest level received during the entire experiment, 155 dB re 1 µPa, occurred at 1503:11.

TABLE 5. Received levels for the vibratory driver.[a]

Location	Maximum[b] dB re 1 μPa	Minimum[b] dB re 1 μPa	Highest mean[c] dB re 1 μPa
Station 1	155	106	150
Station 2	121	86	120
Station 3	116	91	109

[a] In the 25-Hz one-third octave band

[b] Calculated in 1-s intervals

[c] Strongest of mean levels determined across all beam depths

4.2.2 Received levels as a function of range

Mean levels at Stations 2 and 3 were 30–50 dB less than those at Station 1, and were similar to the background levels depicted in Figure 7(a). Estimating how received levels may have varied with range between Station 1 and Stations 2 and 3, however, involves considerable uncertainty, because this part of the Duwamish River does not provide a normal propagation channel for low-frequency sound.

To propagate, underwater sound of a given frequency f requires a minimum water depth inversely related to f. As a rough rule of thumb, the minimum depth required for propagation can be calculated in feet as $1230/f$ (or in meters as $375/f$), where f is given in hertz. A 27-Hz vibratory-driver signal would thus require a channel at least 46 ft (14 m) deep in order to propagate, but the Duwamish in the vicinity of the former Rhône-Poulenc site is at most 33 ft deep. To the extent that the vibratory-beam sounds propagate, therefore, they propagate through the ground, and couple into the water at the riverbed.

To provide a model for received levels in this complex environment, we will assume that they can be represented in the form $\text{SPL} = A + B \cdot \log R$, a widely-used sound-field model, where SPL is the received sound pressure level (typically expressed in dB re 1 μPa) and R is the range to the sound source (typically given in meters). By fitting this model to the highest-mean data listed for Stations 1 and 2 in Table 5, we obtain the expression $\text{SPL} = 238 - 50 \log R$. Figure 9 shows the received levels predicted by this expression as a curve, and compares them with measured levels. While our confidence in the model is low, we do expect that its predictions err on the conservative side, that is, we expect actual received levels generally to be less than those indicated by the curve in Figure 9. Nevertheless great care should be exercised when using values predicted by this model.

4.2.3 Received levels as a function of hydrophone depth

In addition to variation with range, received levels varied with the depth of the receiving hydrophone. Vibratory-driver levels received on the “middle” hydrophone, 6.6 ft (2 m) above the two “bottom” hydrophones (see Table 2) tended to measure 2–6 dB less than those received on the bottom hydrophones. Vibrator levels received on the “upper” (shallow) hydrophone at Station 3, where the water was deep enough to deploy the hydrophone string to its full depth, measured 17–18 dB less than those received on the bottom hydrophones.

A dramatic decrease in SPL with depth is not surprising. The water’s surface releases acoustic pressure to the air, so that sound pressure—the quantity sensed by the hydrophones used in this experiment—falls to zero at the air-water interface. This does not mean, however, that no acoustic field is present. As acoustic pressure diminishes with decreasing depth, vertical acoustic particle velocities increase. Thus those animals sensitive to particle velocity cannot avoid a sound simply by moving towards the surface.

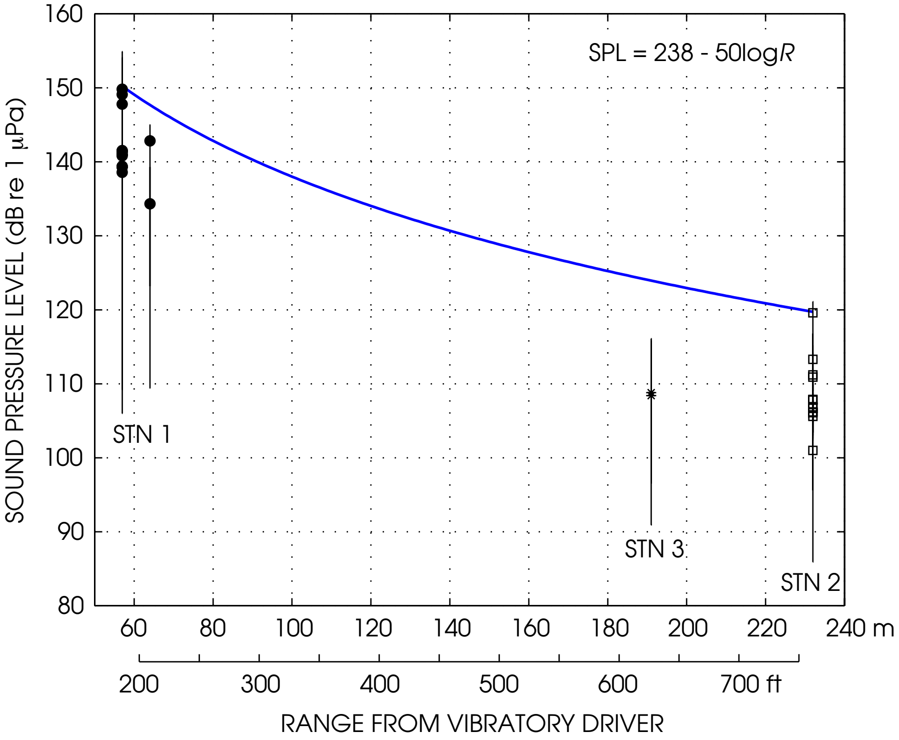

Figure 9. Highest mean received levels predicted between Station 1 and Station 2. For reference, data from Figure 7(b) have been replotted as a function of range to source instead of beam depth.

4.3 PARTICLE VELOCITIES AND ACCELERATIONS

The acoustical literature generally quotes sound levels in terms of acoustic pressure. However, because of the potential sensitivity of some fish to the particle-velocity component of acoustic waves and the need quickly to convert from one form of measurement to the other, we provide a graph that illustrates the relationship (Figure 10). In preparing this graph, a nominal sound speed of 1500 m/s and water density of 1000 kg/m^3 were chosen to represent brackish water. It was also assumed that the signal was propagating in a free field.

Recent literature [*Mueller et al.*, 1998; *Carlson et al.*, 2001] quotes particle motion in terms of acceleration rather than velocity. Figure 11 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 10, but with the additional assumption that the signal in question was a sinusoidal 27-Hz tone. This graph is not appropriate for conversion of background noise levels shown in Figure 7(a) to particle accelerations, because the background noise was neither sinusoidal nor confined to a frequency of 27 Hz.

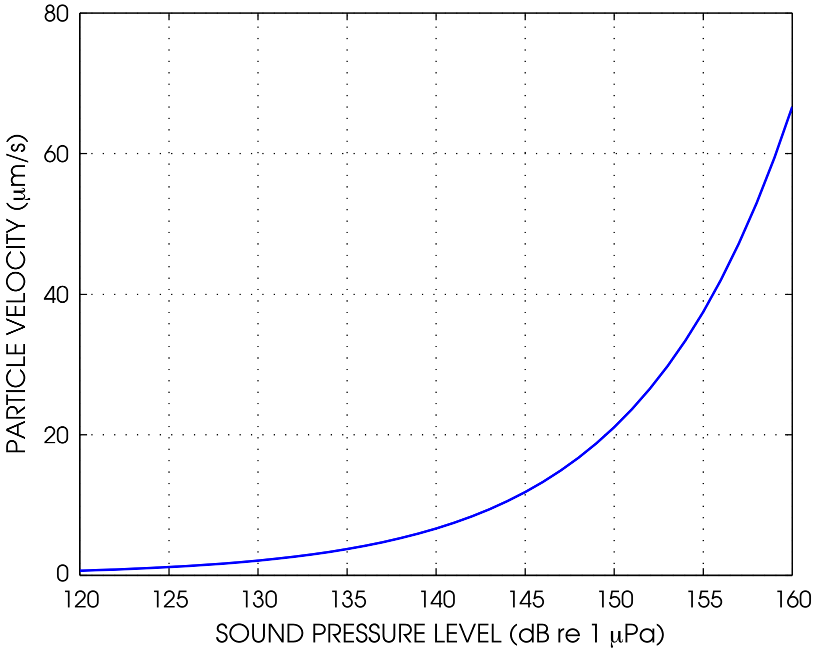

Figure 10. Particle velocity as a function of SPL for an acoustic wave propagating in brackish water.

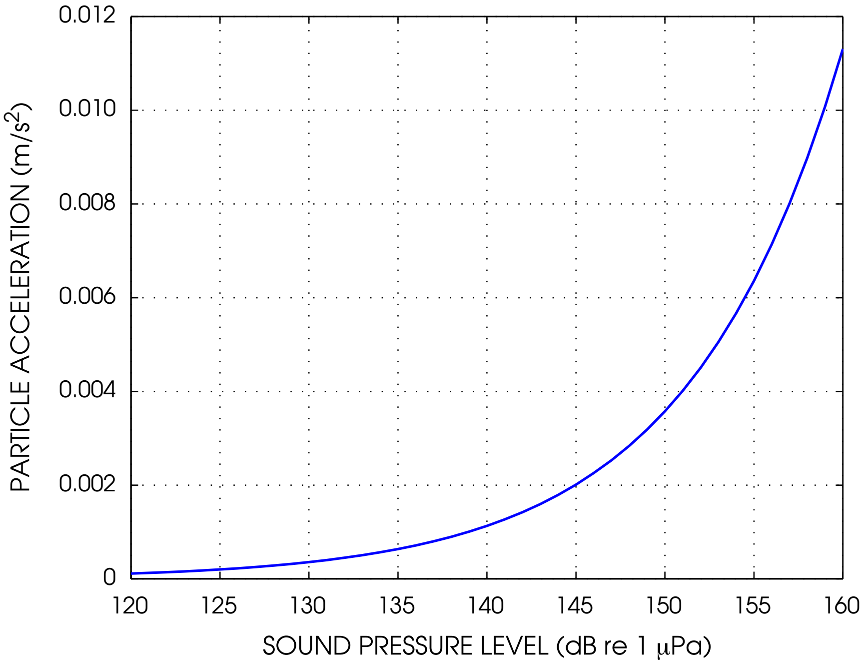

Figure 11. Particle acceleration as a function of SPL for a 27-Hz sinusoid propagating in brackish water.

5 EFFECTS ON SALMONIDS

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 2000 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 hertz [*Coombs et al.* 1989, 1992; *Enger et 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]. The vibratory driver used at the Rhône-Poulenc site in this study produced sounds in the range of frequencies detectable by the lateral line system, but it was positioned on land, 80–100 ft (25–30 m) from the water's edge, and therefore at least that far from any fish. In addition, to our knowledge there are no reports of intense underwater sound causing damage to the lateral line system. Therefore, for the purposes of this discussion we will focus on the effects of sound on fish ears, particularly those of the salmonid family.

5.2 SALMONIDS

The inner ear of a fish contains membranous pouches with sensory hair cells. Based on the orientation pattern of these hair cells, as well as on the type of acoustic coupling between the ear and swim bladder or other gas-filled cavities, fish are classified into hearing "specialists" and hearing "generalists," the latter having in general less sensitive ears [*Popper and Carlson*, 1998].

Salmonids are hearing generalists. The Atlantic salmon (*Salmo salar*) 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 [*Hawkins and Johnstone*, 1978]. High levels of background noise can prevent a fish from detecting a sound source (a phenomenon known as ***masking***), particularly if the background noise occupies the same frequencies as the source. If the frequency of the background noise is different from that of the source, some fish can filter this noise out, but this capability is again notably variable from one species to the next [*Fay*, 1992]. Atlantic salmon, for example, cannot filter out noise that is less than 90 Hz on either side of the frequency of interest [*Hawkins and Johnstone*, 1978].

5.2.1 Audiogram data

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 12 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 $\sim$360 Hz. The threshold level at 27 Hz is therefore (by extrapolation) most likely between 107 and 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.

Station 1 mean levels shown in Figure 7(b) are all well above the 107–115 dB threshold level estimated for Atlantic salmon at $\sim$27 Hz (extrapolated from Figure 12). If we assume that the Atlantic salmon is a representative member of the salmonid family, a salmonid near Station 1 would be almost certain to hear the sounds produced by the vibratory driver. On the other hand, across the river at Station 2, mean levels shown for the 25-Hz one-third octave band in Figure 7(b) are close to the Atlantic salmon's hearing threshold and may not have been more than faintly audible to salmonids in general.

5.2.2 Physiological effects of sound exposure

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 SPLs of 180 dB re 1 μPa. Similarly, exposing goldfish (*Carassius auratus*) for about two hours to SPLs 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]. Also, it is important to note that damage from sound may not appear immediately after the fish is subjected to intense sound [*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 possibly 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 study, sound pressure

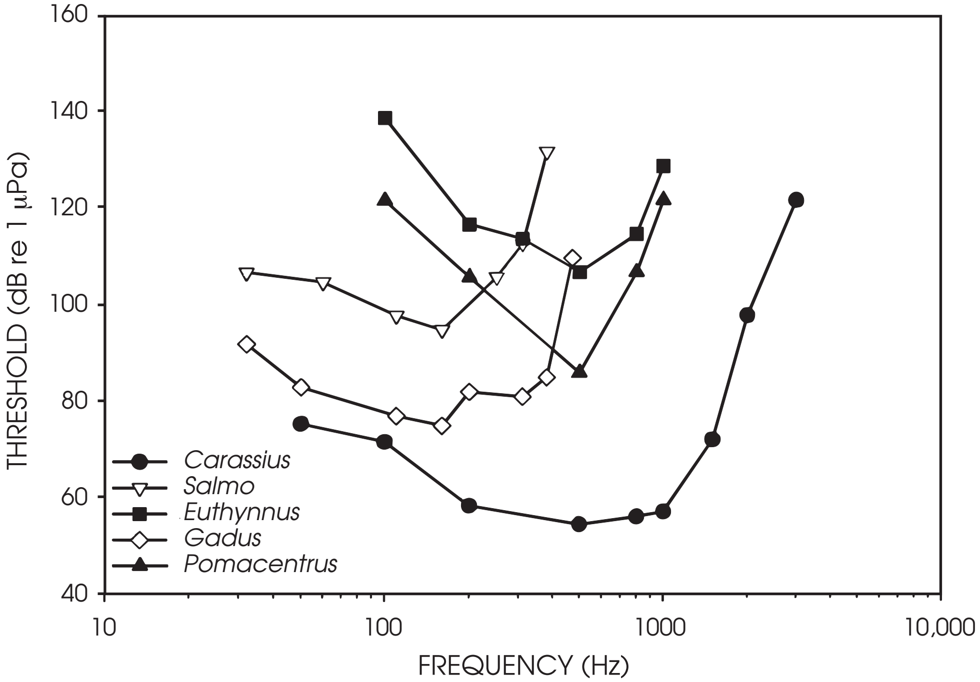

Figure 12. Auditory thresholds of several teleost fish species. All thresholds were determined via behavioral methods in which fish were trained to perform some task whenever they heard a sound. *Carassius auratus* (goldfish) is a hearing specialist (*Jacobs and Tavolga*, 1967) and can detect sounds 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.)*

levels for the one-third octave band centered at 25 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].

5.2.3 Behavioral effects of sound exposure

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 SPLs 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 11 shows that this background-noise acceleration value is about the same as that associated with the strongest sound pressure levels measured in the present study.

One of the few studies in which the response of fish to vibratory pile driving was assessed is that by *Carlson et al.* [2001]. Piles were vibrated in the Columbia River Navigation Channel, directly in the water. The authors concluded that the range from the pile within which they expected the combination of sound pressure levels and particle velocity to result in avoidance reactions was 10–22 ft. Therefore “it appears unlikely that the vibratory pile driving would cause avoidance response by juvenile salmonids beyond the immediate vicinity (20–30 ft) of the pile driving activity, given the conditions observed at the OSU (Oregon State University) pier.” The authors do not give any other details about the vibratory driver other than to mention that the fender piles being driven were steel pipe 60 ft long and of approximately 9-inch diameter.

6 CONCLUSIONS

The vibratory-beam sound levels observed here reflect the strongest levels likely to occur in the Duwamish River from driving operations at the former Rhône-Poulenc site. The vibratory driver was operated at its strongest setting, holes were driven fresh (rather than overlapped with existing holes) for the first two of the three recording stations, and the holes were located at the southwest corner of the site for maximum sound transfer to the water. Sound measurements were made only near high tide, when coupling between the ground and the water would be most efficient. We expect vibratory-beam sound levels during typical operations to be generally less than those measured here.

The levels received at Station 1, the recording station closest to the driver, were below levels discussed in the literature as leading to fish ear damage. Therefore we do not expect the vibratory-beam driving described in this report to cause physiological damage to salmonid fish. Salmonids near Station 1 would, however, have been almost certain to detect the sounds from the vibratory driver. It is difficult to predict how salmonids so exposed might respond, although available data indicate that response may be unlikely. The study by *Burner and Moore* [1962] suggested that to elicit short-term behavioral response from salmonids may require sound levels 20–30 dB higher than those observed here. *Mueller et al.* [1998] used a test tank whose ambient particle accelerations were comparable to those calculated for the strongest signals measured in this study.

If disturbed, salmonids would have the option of moving up, down or across the river, away from the sound source, to areas where the recorded sound pressure levels were only marginally above their hearing thresholds and comparable to the ambient background. Because frequencies produced by the vibratory driver are too low to propagate in the river, the fish would not have to move very far to substantially reduce sound exposure. Avoidance of vibratory-beam sounds near the eastern bank could, however, lead to (1) increased mortality from predators that inhabit the deeper waters, and (2) increased stress on the fish, which is known to reduce growth, increase susceptibility to disease and impair reproduction [*Thomas*, 1990]. On the other hand, salmonid habituation to the vibratory-driver sounds [*Mueller et al.*, 1998] could reduce the incidence of avoidance.

These potential consequences are difficult to quantify; however, given that: (1) vibratory-beam sound levels during normal operations will be generally less than those observed here; (2) even the highest levels measured appear to be below the threshold for salmonid response as it is currently understood in the literature; and (3) the vibratory driving will be temporary, we do not expect the long-term impact of stresses associated with the vibratory driving to be significant compared with those already experienced by the inhabitants of this heavily industrialized river.

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