Final Report: Measurements of Pile Driving Noise from Control Piles and Noise-Reduced Piles at the Vashon Island Ferry Dock

By Peter H. Dahl, Jim Laughlin, and David R. Dall'Osto

Executive Summary

Underwater sound measurements were made on 7 and 8 December 2015 at the Vashon Island ferry dock as the part of the Washington State Department of Transportation (WSDOT) pile attenuation test program. Measurements were made by a University of Washington team aboard the R/V *Robertson* operated by the Applied Physics Laboratory (APL-UW) and by a WSDOT team operating closer to the construction barge.   Another measurement effort was also made closer to the pile by a team from the University of Washington Dept. of Mechanical Engineering. Results from that effort are available a separate WSDOT report.

The goal of the APL-UW team aboard the R/V *Robertson* was to measure the underwater sound field over nearly the entire water column and away from interfering structures, and to make robust estimates of sound mitigation performance of two test pile designs in terms of sound exposure level (SEL) and peak pressure.

Measurements on the R/V *Robertson* were taken at range 120 m from the construction barge complex and pile source location and at water depth 14.8 m using a vertical line array (VLA) that spanned 3.7–11.7 m depth. Results are summarized as follows:

- Comparing the 7 December measurements from the double wall test pile and the control pile shows a reduced peak pressure (8.7–13.5 dB), RMS pressure (8.8–12.7 dB), and SEL (7–10.3 dB).
- Comparing the 8 December measurements from the mandrel test pile and the 7 December measurements from the control pile shows a reduced peak pressure (11.4–14 dB), RMS pressure (10.8–12.6 dB), and SEL (9.3 and 11.1 dB).
- The reduction in peak pressure generally increased as measurement depth on the VLA increased; for the RMS and SEL metrics, no trend was observed.

The WSDOT measurements taken at range 20 m, water depth 8.6 m, and using a single hydrophone system at depth 5.0 m are summarized as follows:

- Comparing the 7 December measurements of the double wall test pile and the control pile shows a reduced peak pressure (12 dB), RMS pressure (10 dB), and SEL (9 dB).

- Comparing the 8 December measurements from the mandrel test pile and the 7 December measurements from the control pile shows a reduced peak pressure (12 dB), RMS pressure (11 dB), and SEL (11 dB).

The APL-UW and WSDOT measurements at respective ranges of 120 m and 20 m from the pile driving source are in good agreement.

Double Wall Test Pile	Peak reduction (dB)	RMS reduction (dB)	SEL reduction (dB)
range 20 m water depth 8.6 m hydrophone depth 5.0 m	12	10	9
range 120 m water depth 14.6 m hydrophone depths 4–12 m	8.7–13.5	8.8–12.7	7–10.3

Mandrel Test Pile	Peak reduction (dB)	RMS reduction (dB)	SEL reduction (dB)
range 20 m water depth 8.6 m hydrophone depth 5.0 m,	12	11	11
range 120 m water depth 14.6 m hydrophone depths 4–12 m	11.4–14	10.8–12.6	9.3–11.1

Measurements from the control pile and both test piles varied over the duration of pile strikes (hundreds of strikes over a duration of minutes); acoustic measurements from the two test piles varied more over the period than the control pile.

The frequency content of the underwater sound changed after about 175 strikes for both the double wall and mandrel test piles. The spectrum band narrowed compared with the spectral characteristics from earlier strikes. Because the change occurred at about the same strike number, and therefore pile depth, it is possible that the substrate encountered at this depth influenced both test piles in the same manner. An alternative explanation is that the steel-framed pile template used to position the piles possibly influenced results; in this case additional underwater sound may have been transmitted via structural paths introduced by metal-to-metal contact between piles and the template.

I. Introduction and Sequence of Events

The original planning documents called for the R/V *Robertson* to be positioned 100 m (Figure 1, proposed anchor 1) from the test pile center and construction barge complex at the Vashon Island ferry dock. Depth at the anchorage site, which is offshore from the eel grass beds, was 14–16 m depending on the tide.

Photographs taken from the R/V *Robertson* and from the Vashon ferry dock (Figures 2 and 3) provide a sense of the physical arrangement of the construction barge complex and the pile center location.

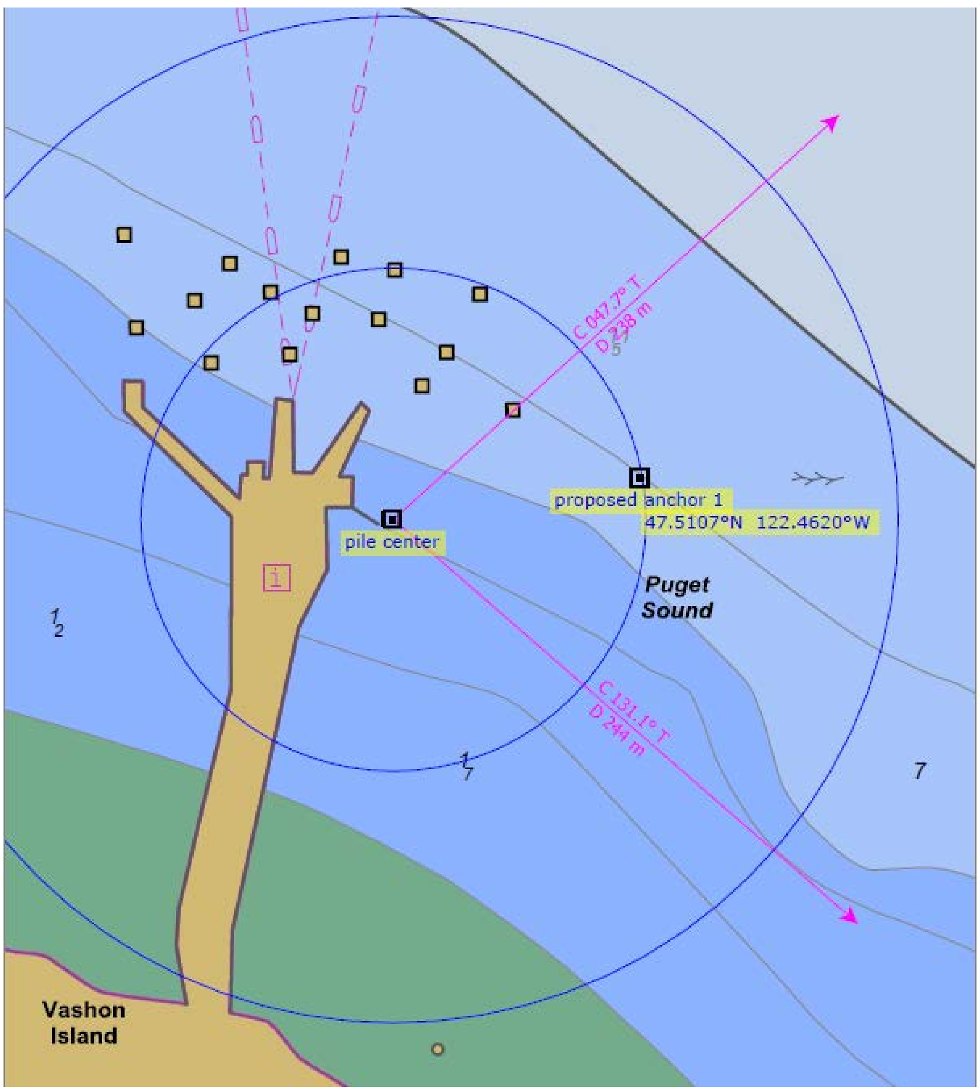


Figure 1. Plan view showing proposed anchor position of the R/V *Robertson* approximately 100 m from the test pile center and construction barge complex. Coarsely-gridded bathymetry (depth in m) is shown with exact, tidal-dependent depths determined at the time of measurements. Wind conditions required final anchor position of the vessel just a few meters farther offshore (see Figure 4) to avoid the fouling of anchor lines with a nearby structures associated with the ferry dock.

Figure 2a. Photograph from the stern of the anchored R/V *Robertson* overlooking the A-frame and looking towards the construction barge complex, taken at 9:00 am on 7 December.

Figure 2b. Photograph taken from the ferry dock looking towards the construction barge complex taken on 7 December. The R/V *Robertson* is seen at a distance in the center of picture.

Figure 3a. Photograph of the placement of the impact hammer on the control pile taken from the R/V *Robertson* on 7 December.

Figure 3b. Photograph of the three piles in the template taken on 8 December. The control pile is on the left, the double wall pile is in the middle, and the mandrel pile is on the right.

The sequence of events for 7 and 8 December 2015 were as follows:

1. Measurements of the **control pile** (30-in diameter) began at approximately noon on 7 December, with a short period of about 50 impact strikes (Measurement Phase 1). This was followed by a period of about 50 min during which the piles were examined and dynamic instrumentation set up, after which an additional 250 impact strikes on the pile were made (Measurement Phase 2).
2. The **double wall test pile** was placed in position and measurements were taken at approximately 2:50–3:10 pm. Impact pile driving and sound measurements occurred in three phases with the first the longest in duration (Measurement Phases 3, 4, 5). This completed the underwater sound test measurements for 7 December.
3. On 8 December the **mandrel test pile** was assembled, positioned, and measurements were taken commencing at 12:47 pm (Measurement Phase 6). This completed the underwater sound test measurements for 8 December.

II. Measurement Geometry and Instrumentation on the R/V *Robertson*

The following acoustic systems were deployed as part of this test:

1. A vertical line array (VLA) was suspended off the A-frame (Figure 2) of the R/V *Robertson*. Hydrophone sensitivity was determined for each hydrophone and accounted for separately with an average of –206 dB re 1 V/μPa. This system recorded with a single hydrophone sampling frequency of 62,500 Hz.
2. An autonomous single hydrophone recording system (Loggerhead) attached to the VLA, with overall sensitivity of –220 dB re 1 V/μPa for the measurements on 7 December and –200 dB re 1 V/μPa for the measurements on 8 December, had a sampling frequency of 50,000 Hz.
3. A single-hydrophone underwater sound level meter (USLM), deployed over the port side of the R/V *Robertson*, had an overall sensitivity of –205 dB re 1 V/μPa and sampling frequency of 52,000 Hz.

The measurement depths of these systems on both days was 1.7–12 m (Figure 4). Note the VLA and Loggerhead systems are in-line, whereas the location of the USLM is offset; the effective range for all systems was approximately 120 m. Additionally, a four-channel geophone/hydrophone system was deployed over the starboard side of the R/V *Robertson*; data from this system are experimental and will not be discussed further in this report.

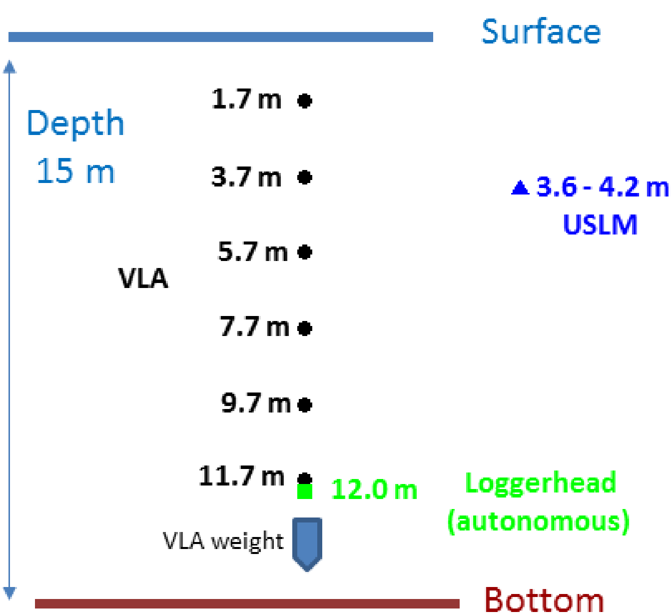


Figure 4. Depth distribution of hydrophones deployed from the R/V *Robertson*. Three systems are shown: vertical line array (black), autonomous Loggerhead system (green), and Underwater Sound Level Meter (blue). This depth distribution applies to 7 and 8 December measurements over the nominal period 12–3 pm.

The R/V *Robertson* was repositioned on 8 December, but the position was within a few meters of the measurement range in effect on 7 December, which is on the order of GPS positioning uncertainty. The water depth on both days, i.e., during the limited time of the measurements and corrected for tides, was 14.8 m as measured by the R/V Robertson depth-sounder and by the sound speed versus depth measurements that yielded a depth-averaged sound speed of 1488.5 m s^{-1} (Figure 6).

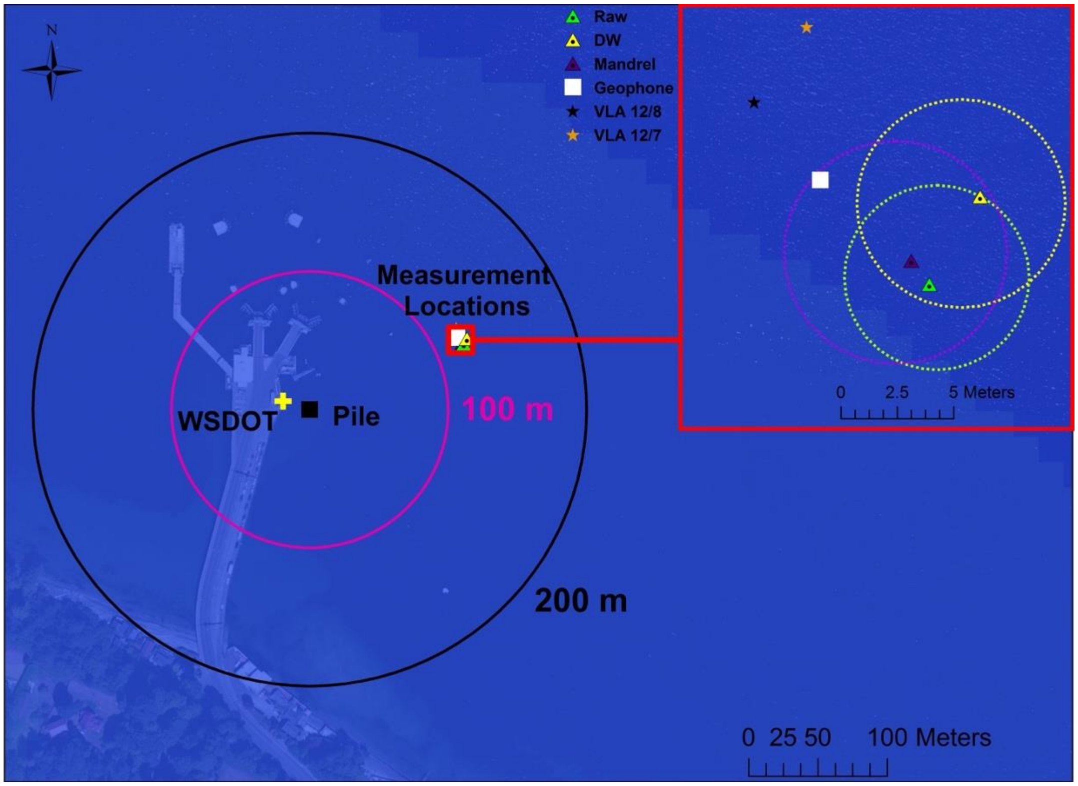


Figure 5. Location for underwater sound measurements made from the R/V *Robertson* (within red box) on 7 and 8 December 2015 at range 120 m from the pile, and by a WSDOT team at range 20 m from the pile. The expanded-scale shows locations on a meter-scale for the Robertson measurements. The three triangular symbols identify the location of USLM measurements for the three pile tests (raw or control pile, DW or double wall pile, and mandrel pile) taken off the port side of the R/V *Robertson*.

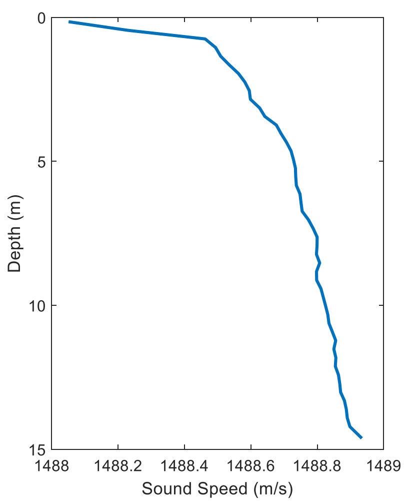


Figure 6. Sound speed vs depth as measured from the R/V *Robertson* on 7 December at 11:30 am. The small reduction in sound speed near the surface at depths less than 2 m is due to a slightly reduced temperature (11.46°C vs 11.56°C at mid-water and near the bottom). The effective water column-averaged sound speed is 1488.5 m s^{-1}. Depth was 14.6 m, to which another 0.2 m was added due to the tide.

III. Results from R/V *Robertson* Measurements

Underwater Sound Level Meter (USLM)

An Underwater Sound Level Meter (USLM) produced by the University of Washington and scheduled for delivery to the Navy was used by permission for an additional measurement from aboard the R/V *Robertson*. Data processing screen shots from the USLM were made immediately after each measurement phase (Figures 7–9); these summarize the six measurement phases of the 2-day test.

The USLM computes the peak pressure and RMS pressure, both expressed in dB re 1 μPa, and SEL, expressed in dB 1 μPa^2-sec (Figure A1). Data from the VLA and Loggerhead recording systems were also processed into these metrics by the same methods.

The file start times are noted in HHMMSS, such as 120034 (Figure 7a). The USLM processing screen shots (Figures 7–9) show the results of all data processed over the measurement period in the lower plots (with colored symbols). The upper plots show pressure measurements for only the last period (about 50 s) of the entire time series.

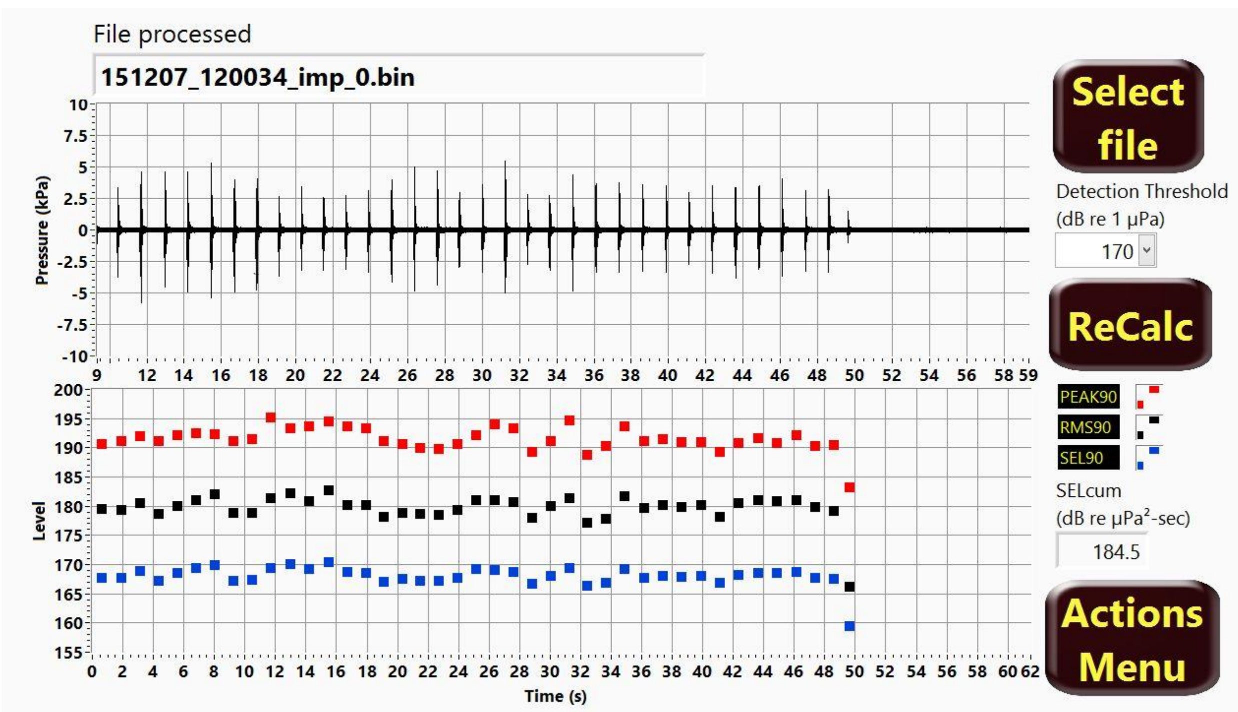


Figure 7a. Phase 1: Results in terms of peak pressure, RMS pressure, and SEL of the first approximately 40 strikes made on the control pile commencing at 12:00 pm on 7 December (lower panel). Note that the time scale of the upper panel, showing raw data, is necessarily different and not all strikes can be shown. The cumulative SEL (SELcum) for these strikes is displayed in the small box, lower right.

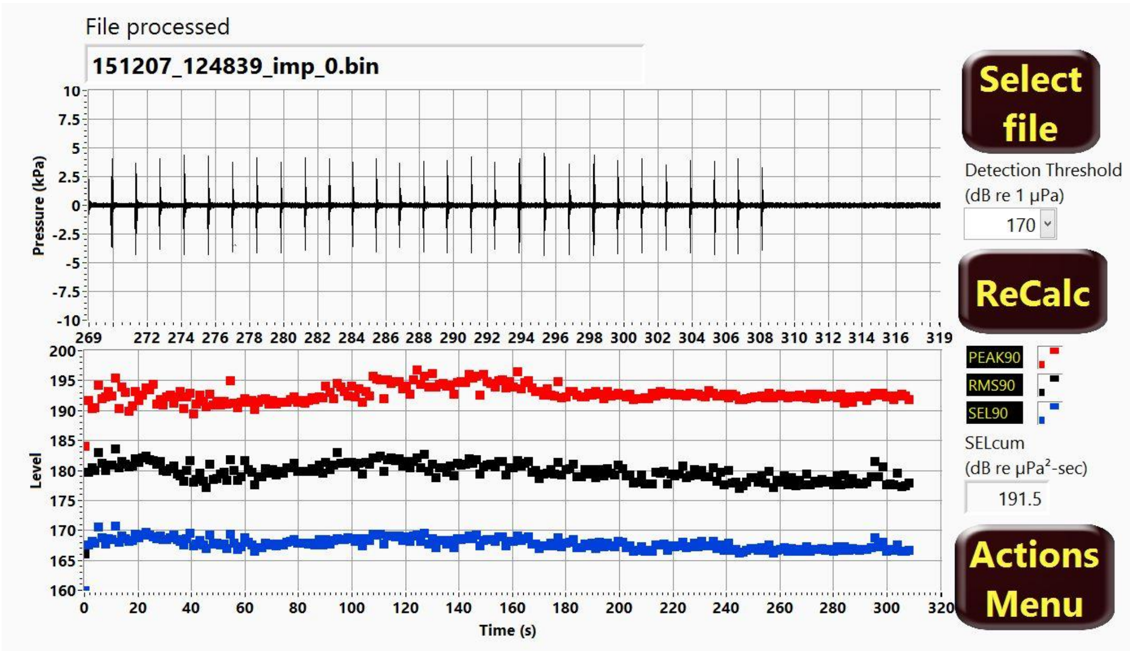


Figure 7b. Phase 2: Results in terms of peak pressure, RMS pressure, and SEL of 231 strikes made on the control pile commencing at 12:48 pm on 7 December (lower panel). Note that the time scale of the upper panel, showing raw data, is necessarily different and not all strikes can be shown. The cumulative SEL (SELcum) for these strikes is displayed in the small box, lower right.

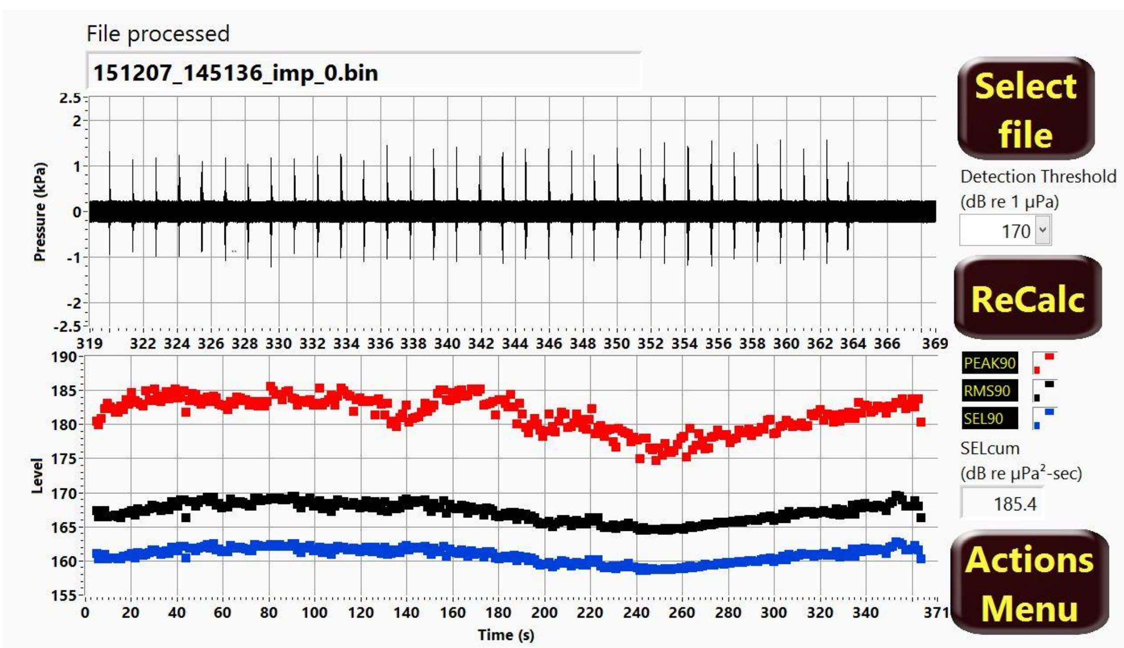


Figure 8a. Phase 3: Results in terms of peak pressure, RMS pressure, and SEL of 272 strikes made on the double wall test pile commencing at 2:51 pm on 7 December (lower panel). Note that the time scale of the upper panel, showing raw data, is necessarily different and not all strikes can be shown. The cumulative SEL (SELcum) for these strikes is displayed in the small box, lower right.

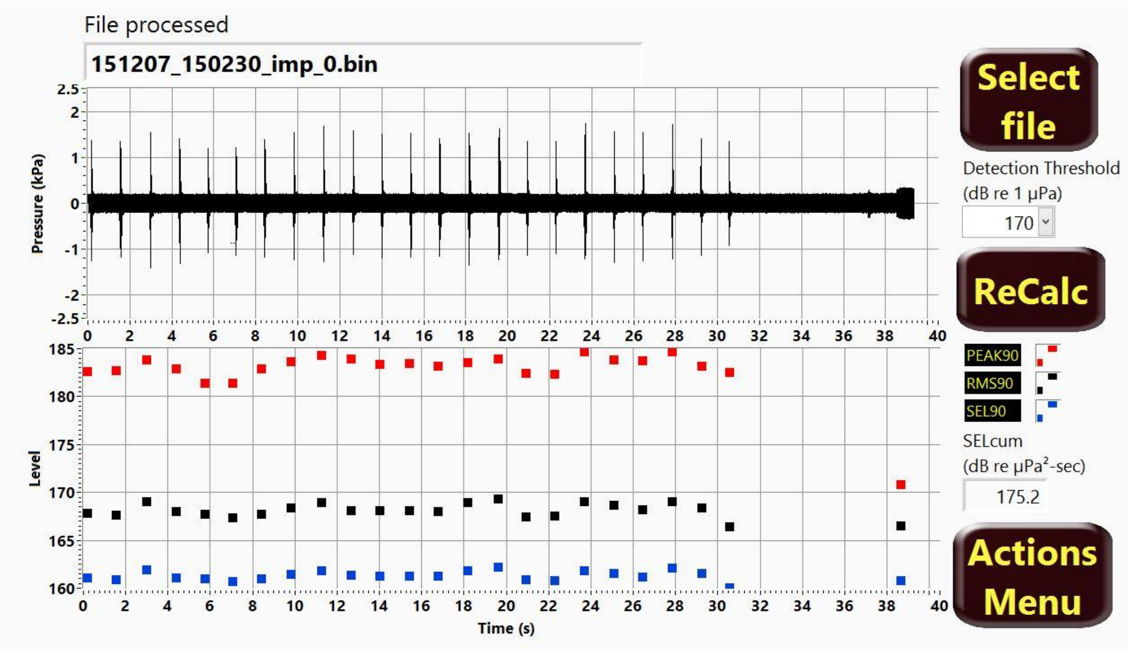


Figure 8b. Phase 4: Results in terms of peak pressure, RMS pressure, and SEL of 23 strikes made on the double wall test pile commencing at 3:02 pm on 7 December (lower panel). The cumulative SEL (SELcum) for these strikes is displayed in the small box, lower right.

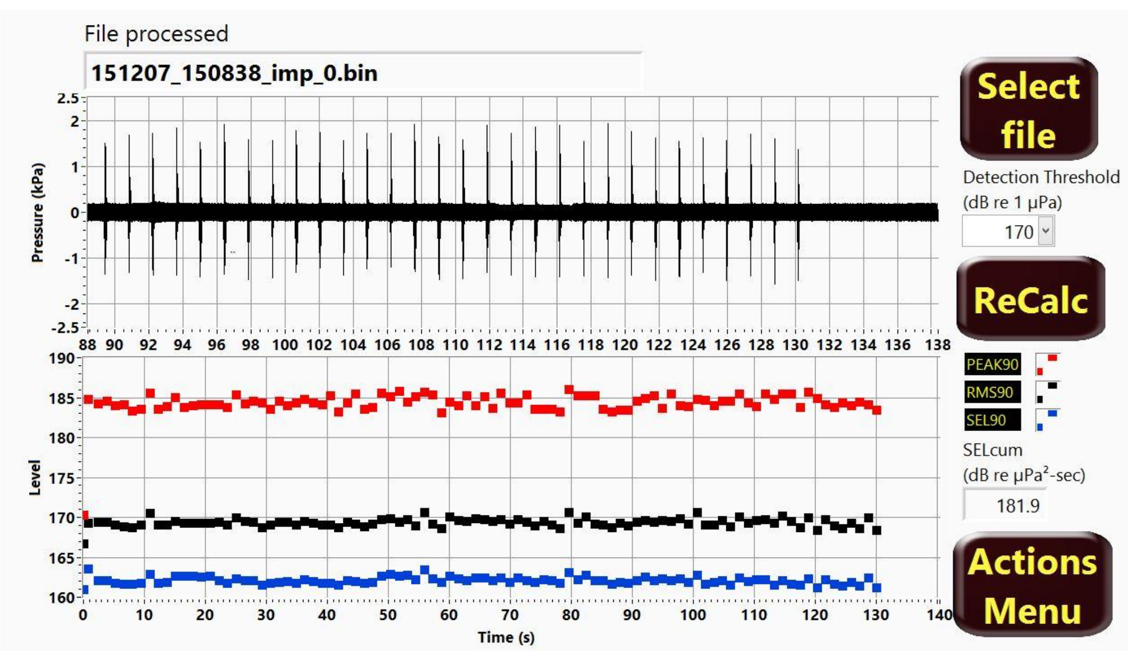


Figure 8c. Phase 5: Results in terms of peak pressure, RMS pressure, and SEL of 95 strikes on the double wall test pile commencing at 3:08 pm on 7 December (lower panel). Note that the time scale of the upper panel, showing raw data, is necessarily different and not all strikes can be shown. The cumulative SEL (SELcum) for these strikes is displayed in the small box, lower right.

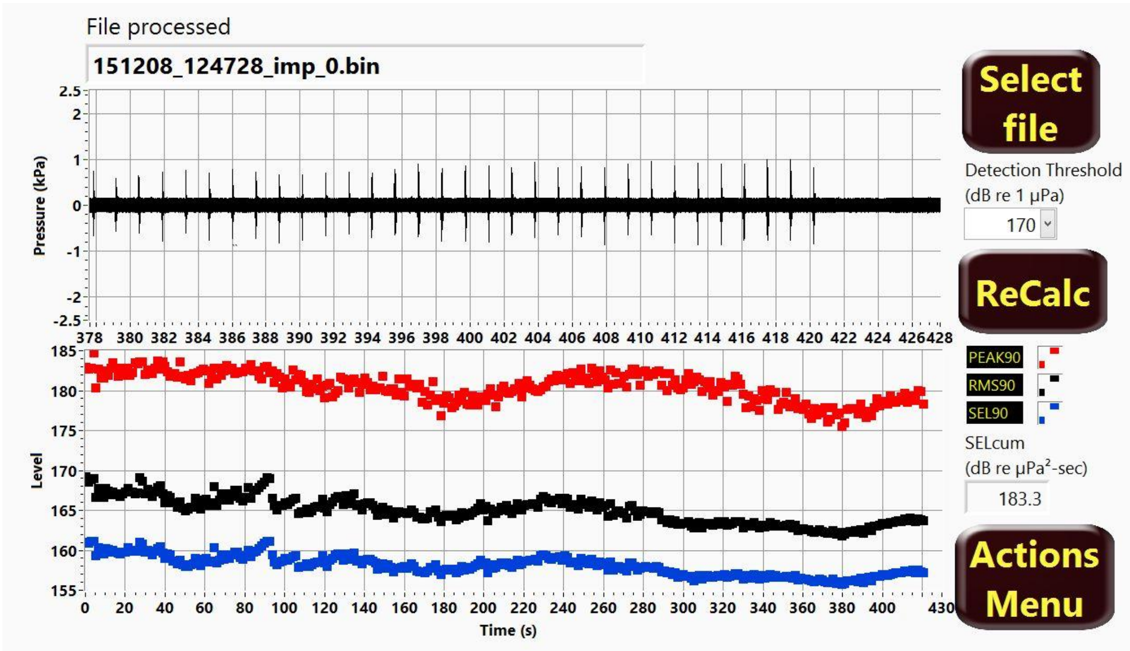


Figure 9. Phase 6: Results in terms of peak pressure, RMS pressure, and SEL of 320 strikes on the mandrel test pile commencing at 12:47 pm on 8 December (lower panel). Note that the time scale of the upper panel, showing raw data, is necessarily different and not all strikes can be shown. The cumulative SEL (SELcum) for these strikes is displayed in the small box, lower right.

Vertical Line Array (VLA)

Measurements from the VLA constitute the key data base for this study. Using the same experimental descriptors established for the USLM, i.e., Measurement Phases 1–6, the evaluation of the VLA data is limited to the longer phases, of order 100 or more pile strikes, obtained in one continuous measurement without pause. These are as follows:

- Control pile on 7 December: Phase 2, 231 strikes
- Double wall test pile on 7 December: Phase 3, 272 strikes; and phase 5, 95 strikes
- Mandrel test pile on 8 December: Phase 6, 320 strikes

As a statistical measure, we use the same convention as the WSDOT — a percentile measure defined as follows. Ln = decibel level exceeded n% of the time during a given measurement period. A single, central or characteristic value from the measurements is L50, with lower bound L90 (exceeded 90% of the time), and upper bound L10 (exceeded 10% of the time). For example, the L10, L50, and L90 values of peak pressure, RMS pressure, and SEL are derived from the 320 corresponding (decibel-based) measurement values for the mandrel test pile, taken over the course of about 420 s.

Here we consider the best measure of the *difference* between control and test pile results, or the best estimate of the noise reduction expressed in decibels. That is, results from the control pile and test pile each yield a probability density function (PDF) of decibel values, and the PDF for the difference value originates from a convolution of these PDFs. It is the L50 of this new PDF that is desired, and we find that the L50 value of the control pile minus that of the test pile, or ΔL50, agrees well with a true L50 generated from numerically convolved PDFs. Thus we (the APL-UW and WSDOT teams) use the difference in L50 values between control and test piles (ΔL50) as the final measure of sound attenuation.

On 7 December the VLA channel at depth 1.7 m (Figure 4) failed owing to a faulty connection. This was remedied for the measurements on 8 December. On that day, data from the 1.7 m channel were similar to the next channel down at depth 3.7 m, but for plotting consistency the 1.7 m channel is not shown.

Appendix B provides a note on measurement uncertainty afforded by the near co-location of the autonomous hydrophone (Loggerhead system) placed 30 cm below the VLA hydrophone at depth 11.7 m (Figure 4).

Figures 10–12 are displayed in the same aspect ratio — the x-axis represents pile strike number such that the evolution over time sound metrics for the control pile (231 strikes) can be compared readily with the test piles that have more strikes.

The figures display VLA data with measurement depth increasing left to right. The three sound metrics peak pressure, RMS pressure, and SEL for a given strike number are shown by the black dots. The gray shaded area encompasses the L90-to-L10 span for each metric and the color-coded solid line identifies the L50 value. For the control pile (Figure 10) there is a slight trend of increasing peak pressure for increasing depth, with the RMS and SEL metrics being less dependent on depth.

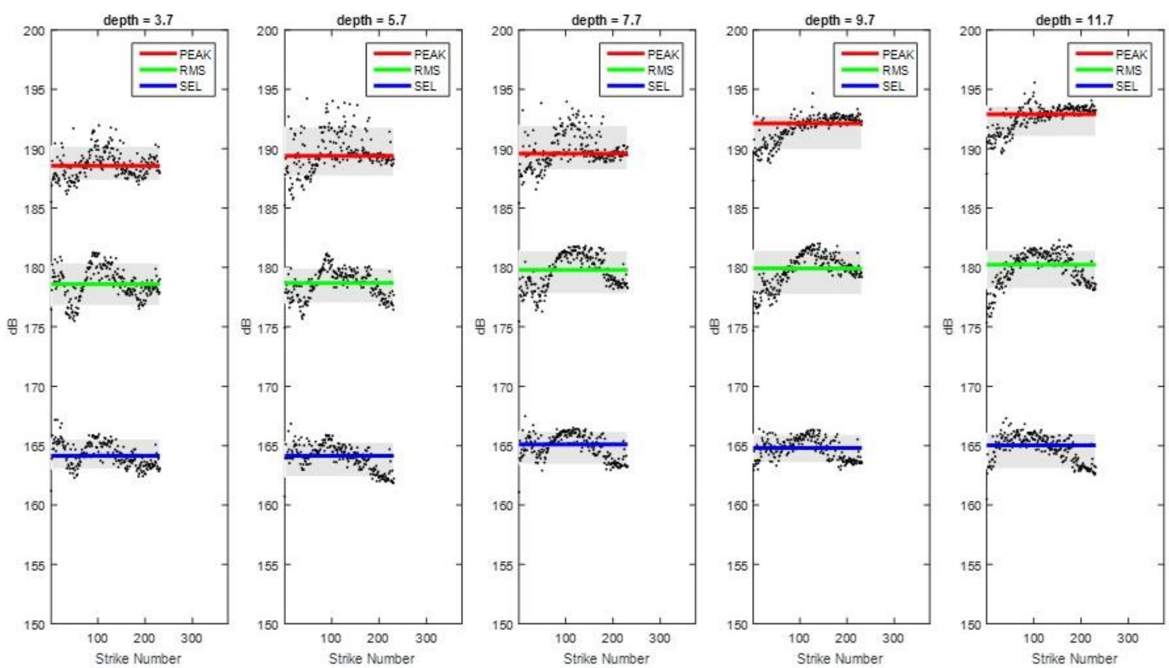


Figure 10. Measurements of the control pile (phase 2) on 7 December. Solid, colored lines denote the L50 value for each metric as identified in the legend, with black dots representing a single strike value. Gray shaded area identifies the range from L90 (lower bound) to L10 (upper bound). Strike number corresponds to impact hammer strike count, with total time duration of the 231 strikes approximately 300 s.

There are two phases (3 and 5) for the double wall test pile, the second commencing approximately 10 min after completion of the first. The short phase in between (phase 4, 23 strikes) was archived by the USLM (Figure 8b). Phase 5 (95 strikes) is plotted with slightly larger symbols starting at strike number 272.

Levels for all three sound metrics during the latter phase (5) form a continuation of the levels from the earlier phase (3). Assuming that pile depth, or position with respect to the frame template, changed very little during the intervening 23 strikes, then this is evidence that underwater noise generation was modulated by pile position.

There is a notable change in the frequency content of the underwater sound from pile strikes commencing at approximately strike 175 for both the double wall (Figure 11) and mandrel (Figure 12) test piles. This change in the frequency spectrum can be described as the spectrum having broadband and narrow-band content, where the latter dominates after strike 175. To evaluate this effect, we compute alternative estimates of L50 based on strikes 1 to 175 that are characterized by a more broadband spectrum (dotted line), and with the remaining strikes characterized by a more narrow-band spectrum (dashed line). The L50 estimates derived from the subset of data characterized by a narrow-band spectrum are typically less than the L50 estimates derived from the broadband data. This result can be anticipated given that a pulse, or strike arrival, with a broader bandwidth will be more peaked in the time domain.

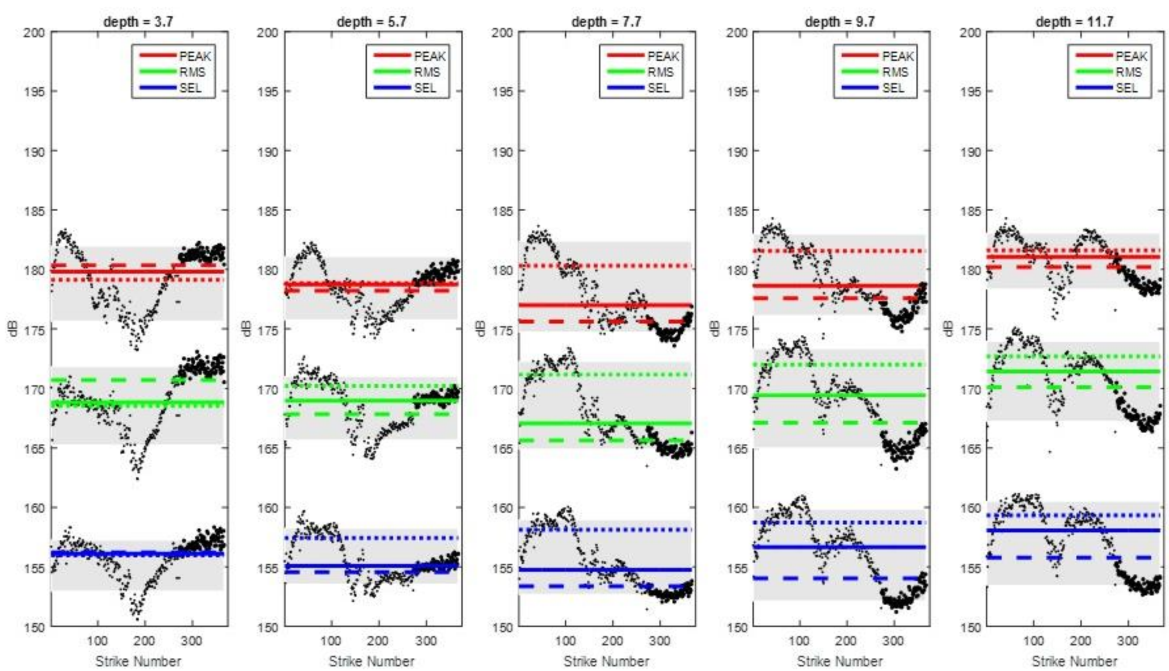


Figure 11. Measurements of the double wall test pile (phases 3 and 5) on 7 December. Solid, colored lines: the L50 value for each metric as identified in the legend. Small black dots: single strike values for phase 3 (272 strikes over about 360 s); larger black dots: single strike values for phase 5 (95 strikes over about 130 s). The dashed and dotted versions of the colored lines represent alternative estimates of L50 based on strikes 1 to 175 characterized by a more broadband spectrum (dotted line), and the remaining 192 strikes characterized by a more narrow-band spectrum (dashed line). Gray shaded area identifies the range from L90 (lower bound) to L10 (upper bound) for the entire set of 367 strikes.

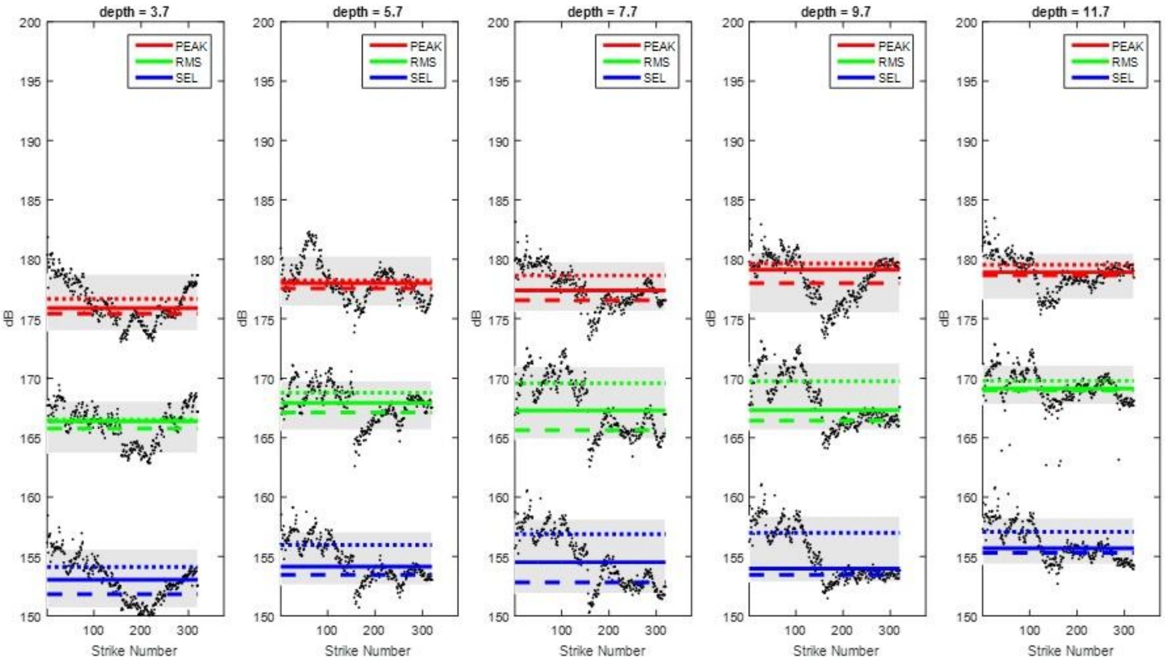


Figure 12. Measurements of the mandrel test pile (phase 6) on 8 December. Solid, colored lines: the L50 value for each metric as identified in the legend. Small black dots: single strike values (320 strikes over about 420 s). The dashed, and dotted versions of the colored lines represent alternative estimates of L50 based on strikes 1–175 characterized by a more broadband spectrum (dotted line), and the remaining 192 strikes characterized by a more narrow-band spectrum (dashed line). Gray shaded area identifies the range from L90 (lower bound) to L10 (upper bound) for the entire set of 320 strikes.

Plotting the energy spectral density of the received signal as a function of strike count for the control and test piles, shows a significant change in frequency content (Figures 13 and 14). The frequency content of data from the control pile (Figure 13, upper) remains largely constant over the sequence of 231 strikes, and is broadly distributed over frequencies less than about 1000 Hz.

In contrast, the frequency content of the double wall test pile (Figure 13, lower plot) changes near strike 175, with the spectrum becoming more concentrated in bands centered around 240 Hz and 375 Hz. That is, as a general observation, prior to strike 175 sound energy is more broadly distributed over frequency whereas after strike 175 energy is more concentrated around the two bands centered at 240 Hz and 375 Hz. This observation also applies to the mandrel test pile, for which after roughly the same number of strikes there is a transition in frequency content (Figure 14, lower plot), which is in agreement with the double wall test pile (Figure 14, upper plot). The reason for this change in frequency content remains under investigation. Because the change occurs at roughly the same strike number, and therefore depth, it is possible that the substrate encountered at this depth influenced both test piles in the same manner.

Note that sound levels measured from the control pile also show a small degree of modulation over the course of the strike history (Figure 10), but this variation is considerably less, with smaller L90-to-L10 ranges, than the test piles. The pile template used to position the piles (Figure 3b) may also influence results from control and test piles insofar as it contributed additional underwater sound transmitted via structural paths introduced by metal-to-metal contact between the piles and the steel-framed pile template.

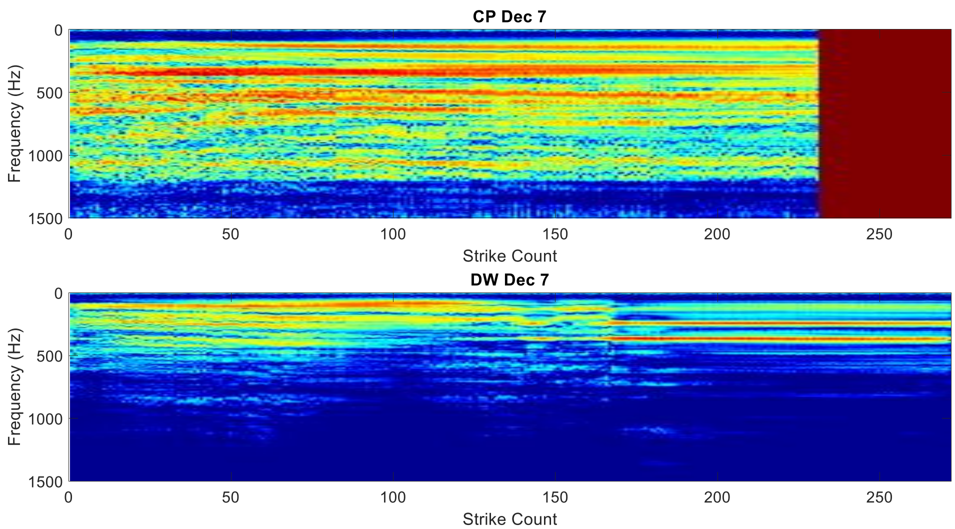


Figure 13. Frequency content of each strike as measured by the Loggerhead system at depth 12 m (in line with the VLA). Upper: the 231 strikes from the control pile (phase 2). Lower: the 272 strikes from the double wall test pile (phase 3). For the double wall test pile the frequency content evolves from a more random, broadband appearance over strikes 1–100, to a transition over strikes 100–175, to one dominated by two narrow frequency bands centered at 240 Hz and 375 Hz over strikes 175–272.

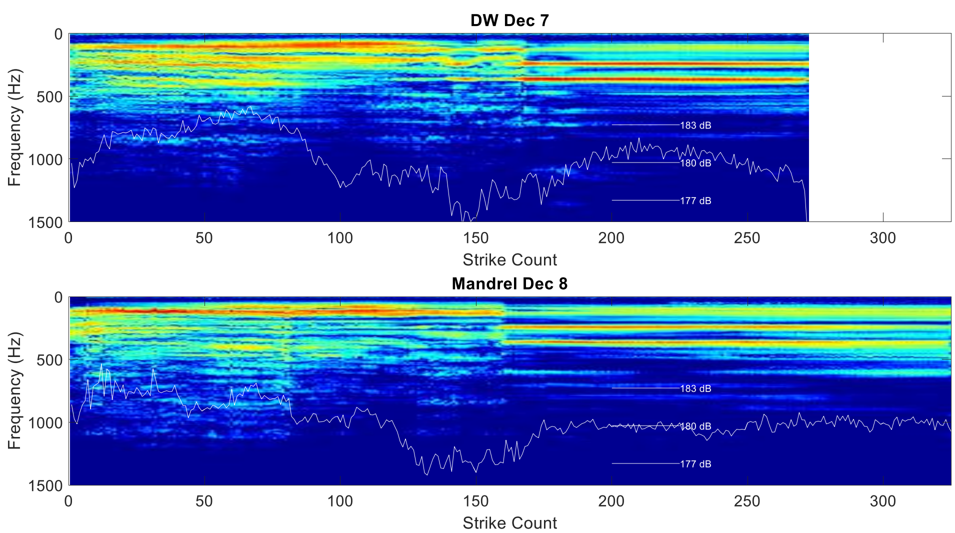


Figure 14. Frequency content of each strike as measured by the Loggerhead system at depth 12 m (in line with the VLA). Upper: the 272 strikes from the double wall test pile (phase 3). Lower: the 320 strikes from the mandrel test pile (phase 6). Superimposed on each graph (thin white lines) is a plot of peak pressure vs strike count.

Figures 15 and 16 present summaries of the calculated L50 and ΔL50 between control and test piles, displayed as a function of depth for the metrics SEL, RMS, and peak pressure. The control pile L50 estimates form the right-hand, higher values (solid lines) with gray shaded areas to identify the extent of the L90–L10 bound.

The double wall test pile (Figure 15) and mandrel test pile (Figure 16) L50 estimates form the left-hand, lower values (solid lines) with gray shaded areas to identify the extent of the L90–L10 bound. The numbers displayed within each panel are the best estimate of noise reduction for each metric as a function of depth. These estimates equal the difference, or ΔL50, in L50 values between the two solid lines at each measurement depth, in decibels rounded to the nearest 0.1 dB.

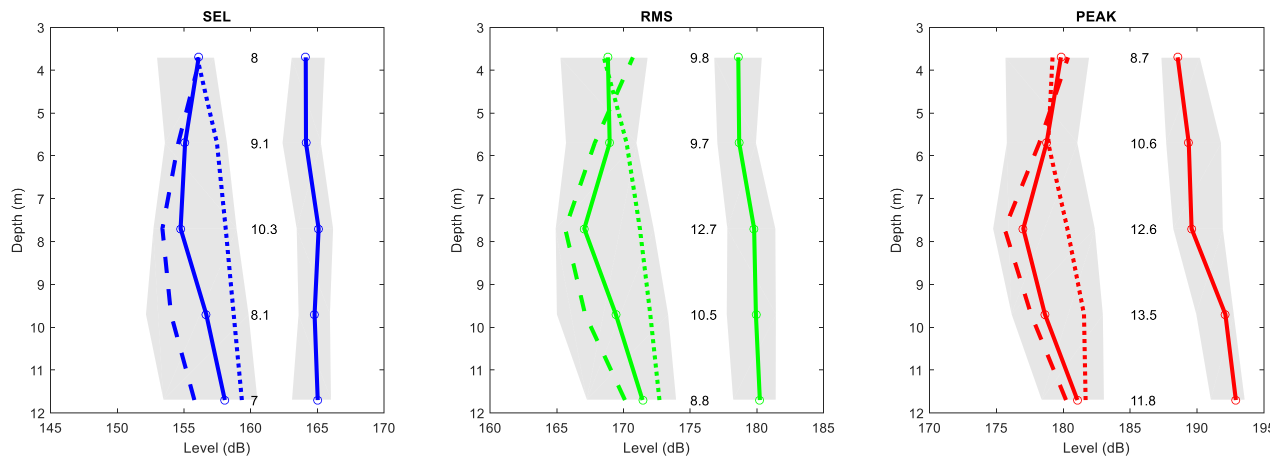


Figure 15. Summary of the double wall test pile noise attenuation measurements as a function of measurement depth, left to right: the metrics SEL, RMS, and PEAK. The control pile measurements form the right-hand or higher values (phase 2). Gray shaded area identifies the L90–L10 bound, and the solid line is L50 as a function of depth (symbols at exact depth). The double wall test pile measurements form the left-hand or lower values (phases 3 and 5). Gray shaded area identifies the L90–L10 bound and the solid line is L50 as a function of depth. The numbers within the panels are the best estimate of noise reduction for each metric as a function of depth. These estimates equal the difference, or ΔL50, in L50 values between the two solid lines at measurement depth, in decibels rounded to the nearest 0.1 dB. The dashed and dotted versions of the colored lines represent alternative estimates of L50 for the test pile case.

The dashed and dotted versions of the colored lines represent alternative estimates of L50 for the test pile cases, for which strike data is characterized by a broader band spectrum (dotted line), or by a narrower band spectrum (dashed line). They are included here only to assess the influence of the received underwater noise spectral characteristics on noise reduction. However, viewed in this manner we also observe that the L50 line tends to be less dependent on depth for the broadband subset of data (dotted), than the L50 lines derived from narrow-band subset of data (dashed). All data included in this subset tend toward a minimum at the measurement depth of 7.7 m. This is likely a waveguide effect, where at depth ~15 m, the two dominate frequency bands, near 240 Hz and 375 Hz, are supported by 2 and 3 underwater waveguide normal modes, respectively. The receiver at depth 7.7 m is near a zero-crossing, or null, of mode 2 for both these frequencies and therefore we anticipate a reduced level at this depth. When the spectrum is more broadband this effect will be muted.

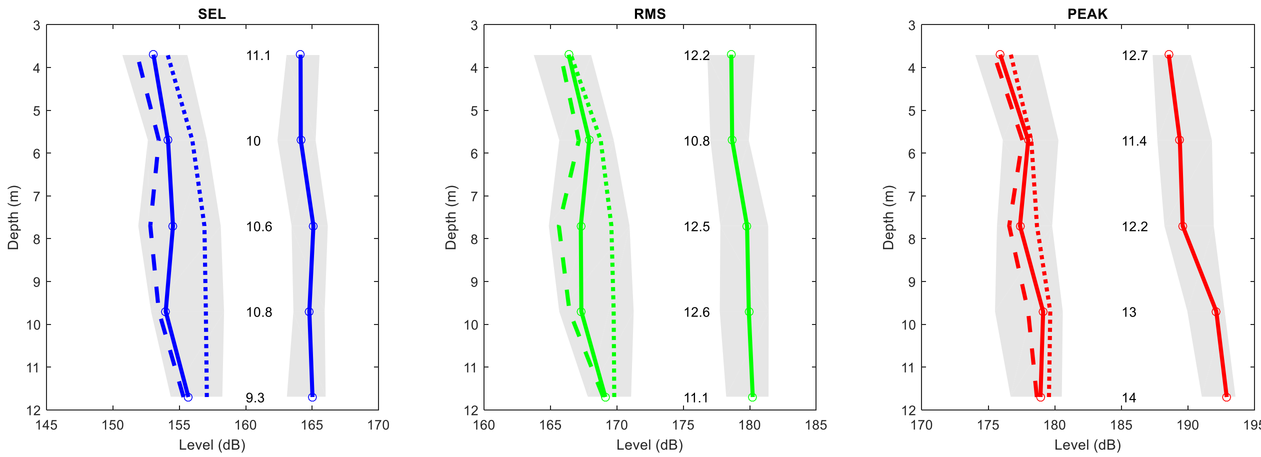


Figure 16. Summary of the mandrel test pile noise attenuation measurements as function of measurement depth, left to right: the metrics SEL, RMS and PEAK. The control pile measurements form the right-hand or higher values (phase 2). Gray shaded area identifies the L90–L10 bound and the solid line is L50 as a function of depth (symbols at exact depth). The mandrel test pile measurements form the left-hands or lower values (phase 6), with the solid line the L50 as a function of depth and gray shaded area the L90–L10 bound. The numbers within the panels are the best estimate of noise reduction for each metric as a function of depth. These estimates equal the difference, or ΔL50, in L50 values between the two solid lines at measurement depth, in decibels rounded to the nearest 0.1 dB. The dashed and dotted versions of the colored lines represent alternative estimates of L50 for the test pile case.

IV. WSDOT Measurements

The WSDOT measurements of the control and double wall test piles on 7 December (Figures 17–22) and the mandrel test pile on 8 December (Figures 23–25) were made using an autonomous single hydrophone recording system with sensitivity of –211 dB re 1 V/μPa and sampling frequency of 48,000 Hz. The hydrophone was positioned at range 20 m (Figure 5) and approximate depth 5.0 m in water that was 8.6 m deep based on tidal conditions in effect between about 12:00 and 2:00 pm.

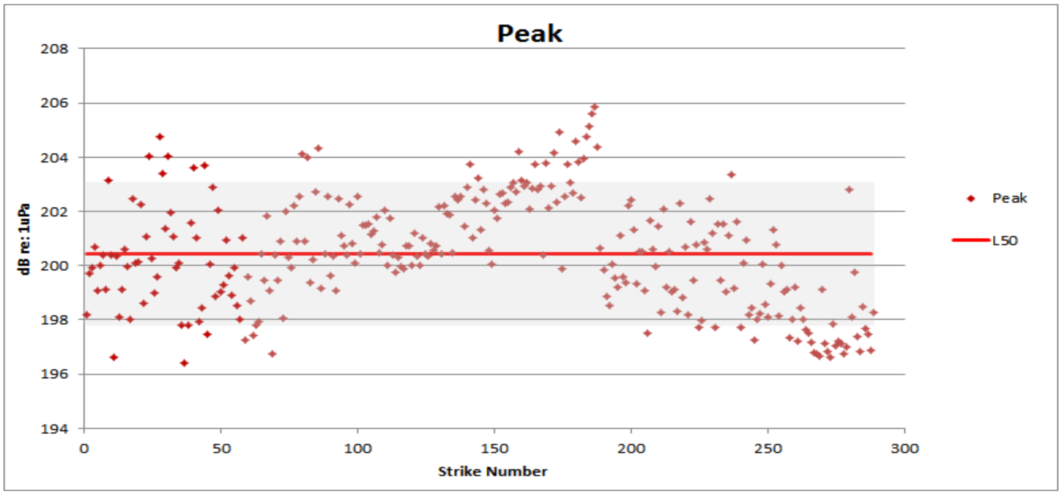


Figure 17. Summary of the control pile measurements made on 7 December for peak pressure at range 20 m and depth 5.0 m. The shaded area represents the L10–L90 bound and solid line the L50 value.

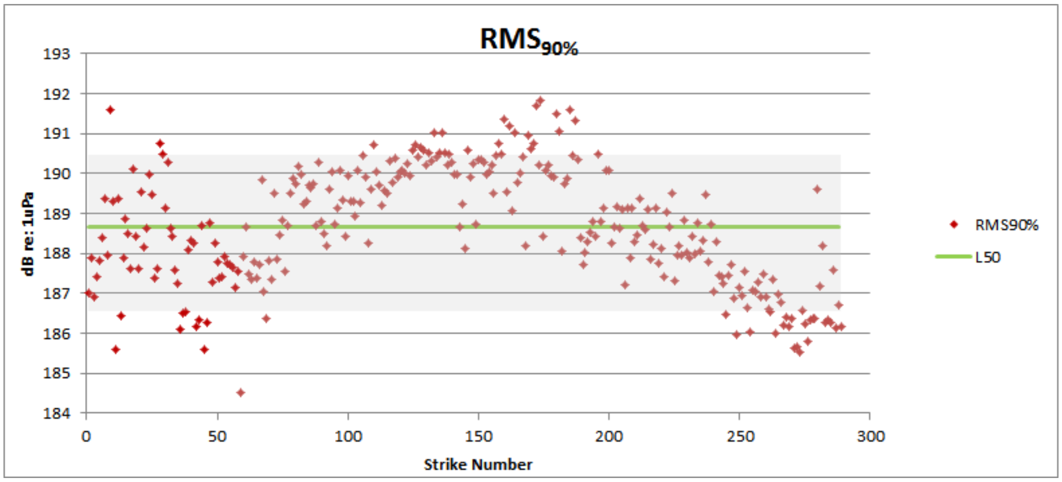


Figure 18. Summary of the control pile measurements made on 7 December for RMS pressure, at range 20 m and depth 5.0 m. The shaded area represents the L10–L90 bound and solid line the L50 value.

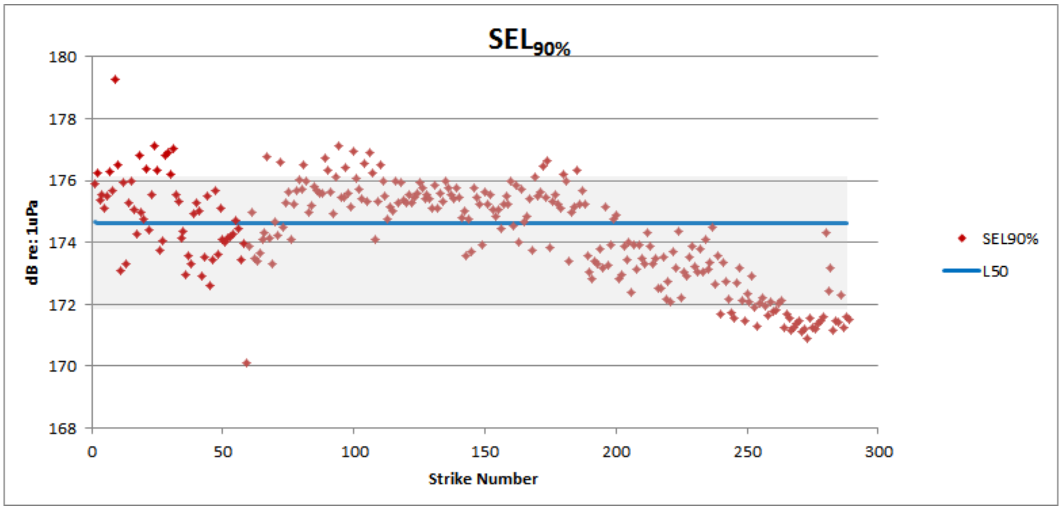


Figure 19. Summary of the control pile measurements made on 7 December for SEL, at range 20 m and depth 5.0 m. The shaded area represents the L10–L90 bound and solid line the L50 value.

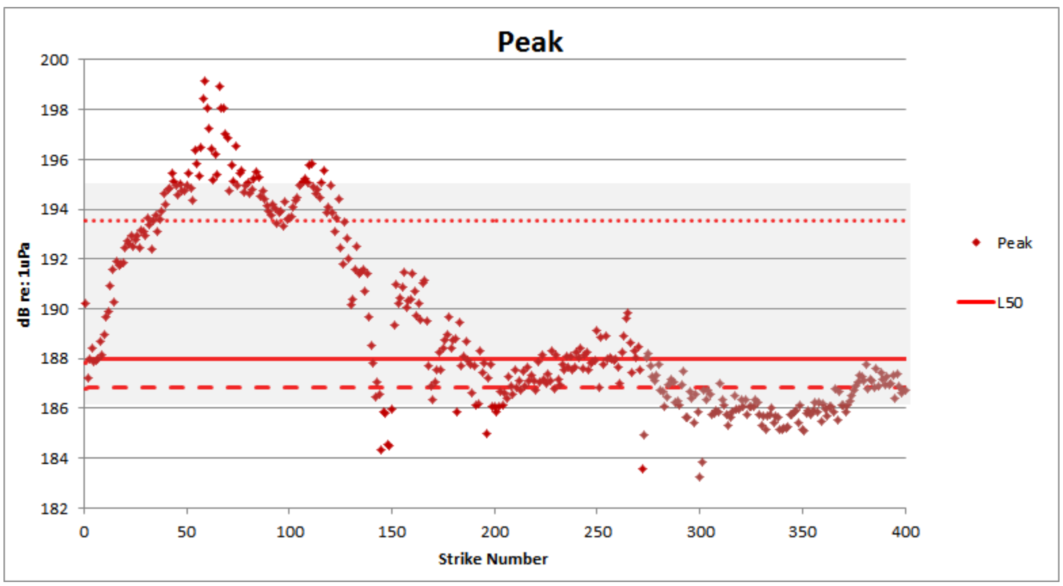


Figure 20. Summary of the double wall test pile measurements made on 7 December for peak pressure, at range 20 m and depth 5.0 m. The shaded area represents the L10–L90 bound and solid line the L50 value, dotted line is L50 for the first 175 strikes, dashed line is L50 for strikes after 175.

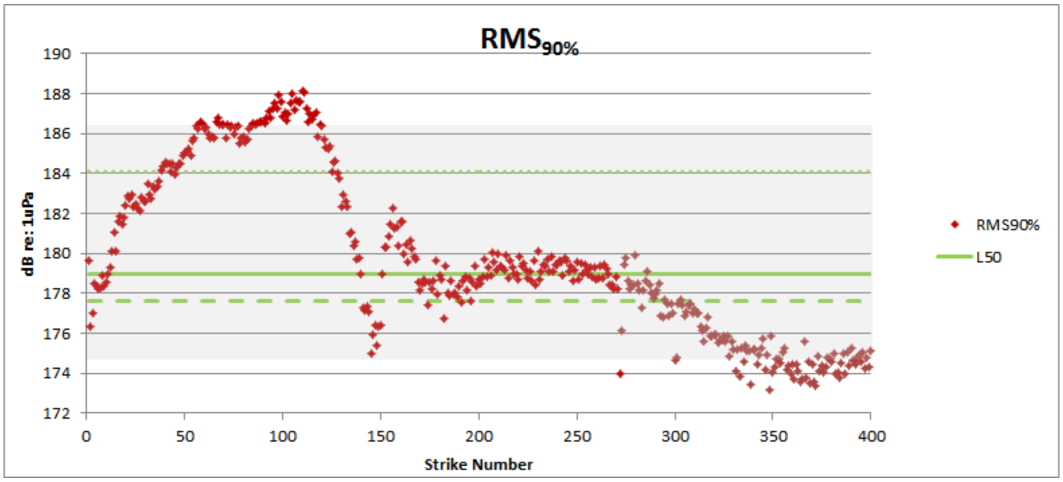


Figure 21. Summary of the double wall test pile measurements made on 7 December for RMS pressure, at range 20 m and depth 5.0 m. The shaded area represents the L10–L90 bound and solid line the L50 value, dotted line is L50 for the first 175 strikes, dashed line is L50 for strikes after 175.

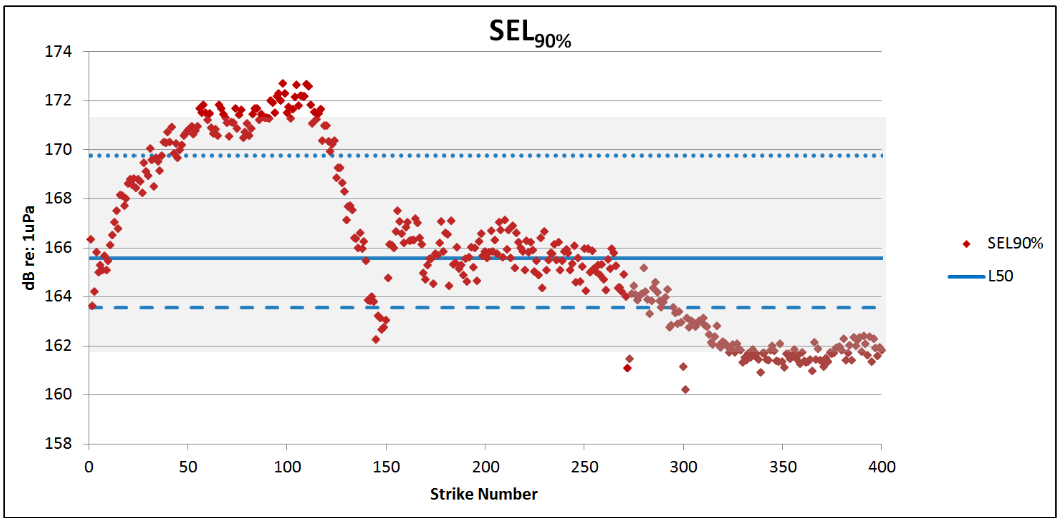


Figure 22. Summary of the double wall test pile measurements made on 7 December for SEL, at range 20 m and depth 5.0 m. The shaded area represents the L10–L90 bound and solid line the L50 value, dotted line is L50 for the first 175 strikes, dashed line is L50 for strikes after 175.

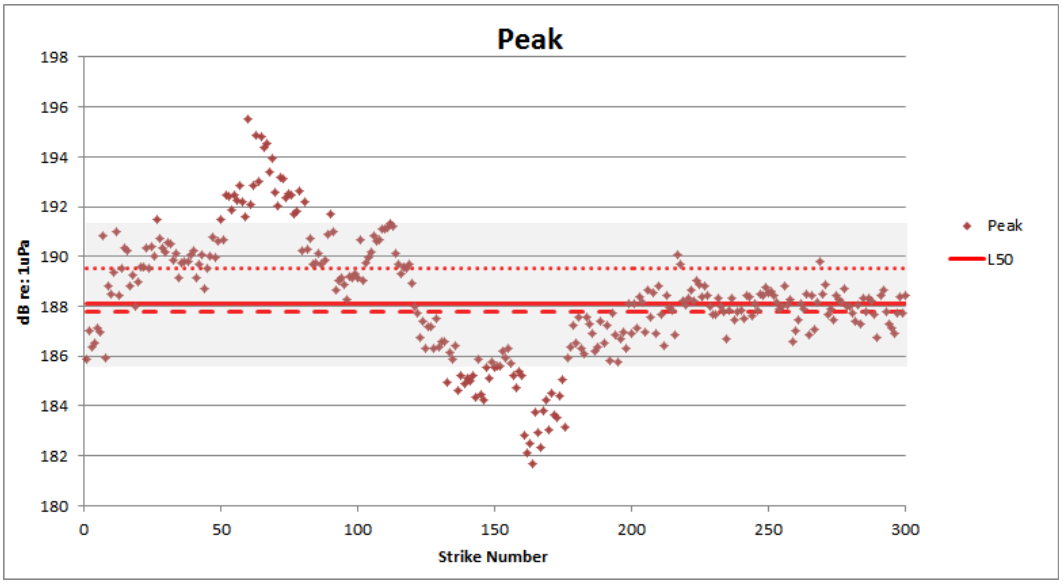


Figure 23. Summary of the mandrel test pile measurements made on 8 December for peak pressure, at range 20 m and depth 5.0 m. The shaded area represents the L10–L90 bound and solid line the L50 value, dotted line is L50 for the first 175 strikes, dashed line is L50 for strikes after 175.

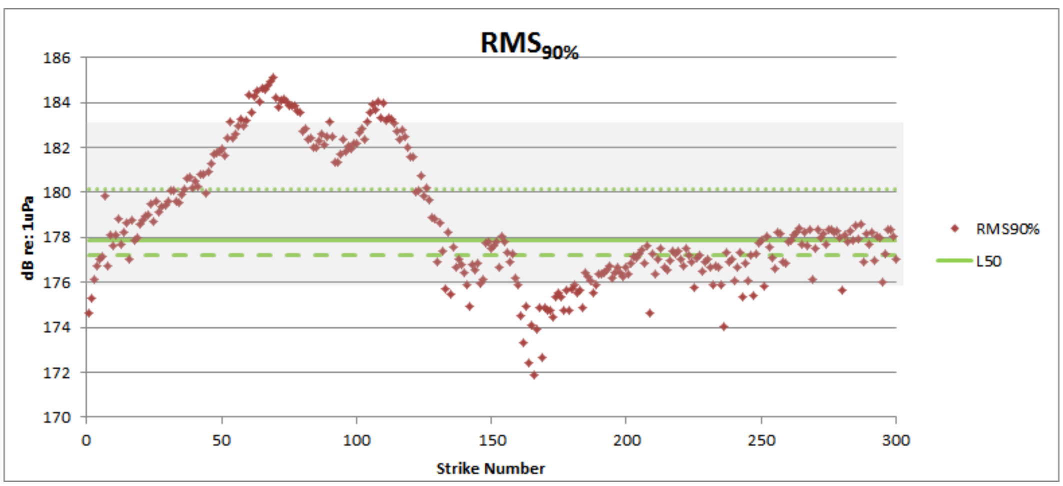


Figure 24. Summary of the mandrel test pile measurements made on 8 December for RMS pressure, at range 20 m and depth 5.0 m. The shaded area represents the L10–L90 bound and solid line the L50 value, dotted line is L50 for the first 175 strikes, dashed line is L50 for strikes after 175.

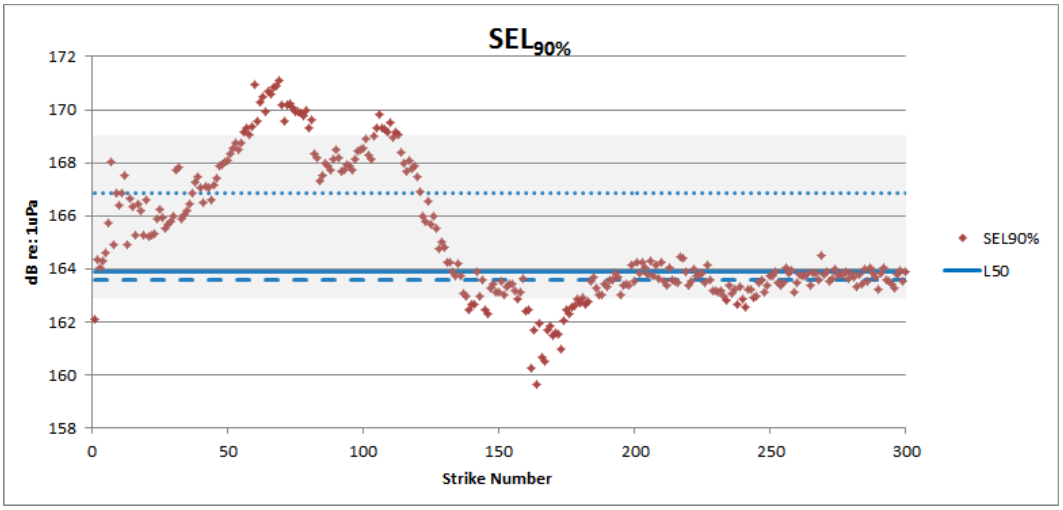


Figure 25. Summary of the mandrel test pile measurements made on 8 December for SEL, at range 20 m and depth 5.0 m. The shaded area represents the L10–L90 bound and solid line the L50 value, dotted line is L50 for the first 175 strikes, dashed line is L50 for strikes after 175.

The WSDOT data were examined by the same methods as the VLA data to yield results in terms of decibel noise reduction of peak, RMS, and SEL metrics as determined by the ΔL50 between control and test piles.

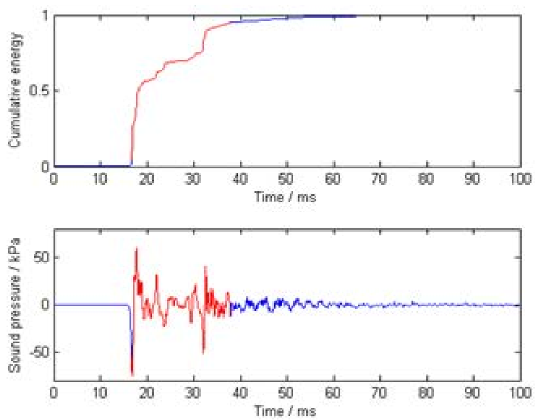
Double Wall Test Pile	Peak reduction (dB)	RMS reduction (dB)	SEL reduction (dB)
range 20 m water depth 8.6 m hydrophone depth 5.0 m	12	10	9

Mandrel Test Pile	Peak reduction (dB)	RMS reduction (dB)	SEL reduction (dB)
range 20 m water depth 8.6 m hydrophone depth 5.0 m,	12	11	11

Acknowledgments

This research was supported by the Washington State Department of Transportation (WSDOT). The authors thank Rhonda Brooks, Marion Carey and Jon Peterson of WSDOT for their support of this effort, and Per Reinhall and Tim Dardis of the University of Washington for their efforts in arranging for the December field test.

Appendix A: Determination of RMS and SEL Measures



$$\mathrm{SEL}_{90} = 10\log_{10}\left(\int_{T_5}^{T_{95}} \frac{p(t)^2}{p_{\mathrm{ref}}{}^2 t_{\mathrm{ref}}}\,\mathrm{d}t\right)$$

Figure A1. Illustrating the definition of the time span corresponding to 90% of the energy of a broadband pulse. The time span, red segment in lower left panel, is determined by squaring and integrating the pulse in a cumulative sense (upper left panel) after which the 0.05-to-0.95 energy time duration is determined. SEL is then computed over this time duration as shown in right panel, and this same time duration is used to compute the RMS pressure.

Appendix B: A Note on Acoustic Measurement Uncertainty

An autonomous hydrophone (Loggerhead systems) was placed at depth 12 m, or 30 cm below the deepest hydrophone (11.7 m) on the VLA (Figure 4). This allowed for a reasonably co-located comparison between two completely separate recording systems.

For the control pile measurements (7 December), the L50 value peak pressure derived from the Loggerhead system exceeded the corresponding L50 value derived from channel 1 of the VLA (11.7 m) by 0.7 dB. For the mandrel test pile measurements (8 December) the Loggerhead system L50 value exceeded that from channel 1 of the VLA by 1.3 dB. Such small differences are very encouraging in view of the fact that these measurements are made down-range of a source by more than 100 m, and that it is difficult to calibrate a *single* hydrophone to a precision better than +/– 1 dB (see http://www.npl.co.uk/upload/pdf/uncertainty.pdf) let alone two independent hydrophones.

In terms of the noise reduction (peak pressure) metric, or the difference between L50 values from the control and mandrel test pile measurements, the Loggerhead system data put this value at 13.4 dB, and channel 1 of the VLA data put this value at 14.0 dB (Figure 16, right panel).