Measurement of Impact Pile Driving Noise from Prototype Piles in Commencement Bay, Tacoma, Washington

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Executive Summary

Underwater noise measurements for the purpose of evaluating the noise reduction performance of two new pile designs from the University of Washington were conducted on October 29-30, 2014 in Commencement Bay in cooperation with the Washington State Department of Transportation and Port of Tacoma.

Measurements of the underwater noise from impact pile driving were first made using a standard, 30-inch pile (October 29th) followed by measurements on two reduced-noise pile designs both involving 30 inch piles; one a double-walled prototype (October 29th) and the other double-walled mandrel prototype (October 30th).

Measurements were made at a range of 8 to 8. 5 m from the piles using a 9-element vertical line array (VLA) and at two remote locations, at 122 m and 502 m (October 29th) and at 135 m and 535 m (October 30th). The underwater sound metrics used for comparison were the peak (absolute value) pressure (PEAK) in dB re 1 μPa, the root mean square pressure over time period covering 90% of pulse energy (RMS) in dB re 1 μPa, the Sound Exposure Level (SEL) in dB re 1 μPa^2-sec. Of these metrics, SEL is the most robust and noise reduction of approximately 18 dB is observed. Higher levels of reduction in the PEAK (21-23 dB) were observed at the VLA site but not at the distant sites. The reduction occurred over a broad frequency range (Appendix A) and was not frequency selective.

In terms of permitting, On October 29th a total of 185 pile strikes were made. At the remote range of 122 m the cSEL was determined to be 183 dB re 1 μPa^2 sec, based on computation of the single SELs for all strikes (Appendix B). Based on the modeling the estimated range to the 187 dB cSEL isopleth was approximately 60 m. On October 30th, there were a total of 70 strikes of much lower energy level (because unmitigated control pile was not used) and cSEL was estimated to be 184 dB re 1 μPa^2 sec at range of about 8 m, setting the 187 dB cSEL isopleth range to be less than 10 m.

I. Introduction

This report summarizes the results of underwater noise measurements for the purpose of evaluating the noise reduction performance of two new pile designs from the University of Washington as part of a research effort funded by the Washington State Department of Transportation and FHWA.

The Port of Tacoma has joined the research effort by identifying a test site in Commencement Bay (Fig. 1) for field testing and assisting with the permit process. Tests were conducted on October 29-30, 2014.

The tests are divided into three basic phases the first two conducted on October 29th and the third phase on October 30th:

(1) A standard 30-inch diameter steel pile as the control pile (CP). During the first part of this test an industry standard unconfined bubble curtain was cycled on and off to also measure the noise reduction efficiency of the bubble curtain.

(2) Test Pile 1: A 30-inch diameter steel double-walled prototype pile (DWP)

(3) Test Pile 2: A 30-inch diameter steel double-walled prototype mandrel pile (MP)

Additional details relating to the three phases are given in Sec. IV.

Figure 1. Vicinity map of Prototype Pile Test Project in Commencement Bay (blue shaded area).

II. Fixed Underwater Acoustic Measurement Locations and Geometry

Underwater acoustic measurements were made at three locations designed to measure underwater sound over an unobstructed propagation path between pile source and acoustic receiver. The first was a 9-element vertical line array (VLA) with hydrophone separation of 0.7 m. Hydrophone sensitivity was determined for each hydrophone and accounted for separately with average being -206 dB re 1 V/μPa. This system recorded with a single hydrophone sampling frequency of 62500 Hz. The position of the VLA with respect to the three test piles and barge complex is sketched in Fig. 2, photographs of the three piles made in shortly after testing on October 30th are shown in Figs. 3a and 3b. The relative position of the 9 hydrophones within the water column is shown in Fig. 4.

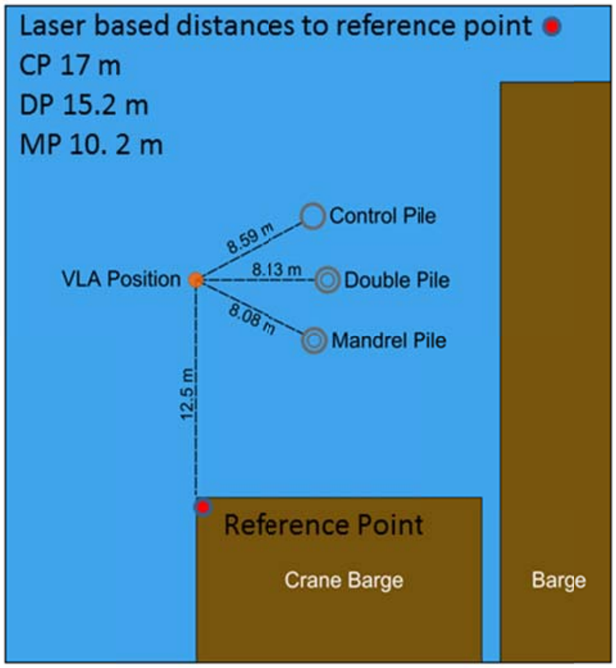


Figure 2. Position of the VLA with respect to the three test piles and barge complex.

Figure 3a. Photograph made on October 30th of the 3 piles shown in order of nearest to farthest: Mandrel Pile, Double Pile and Control Pile. Buoy marker on left shows approximate position of the VLA.

Figure 3b. Photograph made on October 30th of the 3 piles shown in order of nearest to farthest: Mandrel Pile, Double Pile and Control Pile. The VLA, now under tension is shown on the left while its range from the piles is measured.

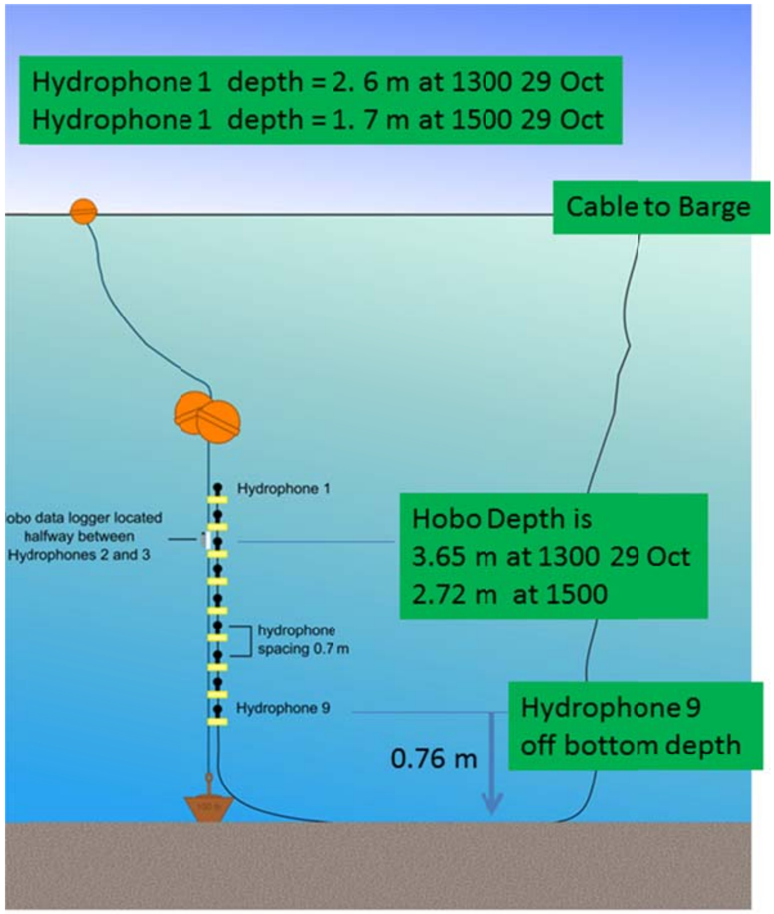


Figure 4. Position of the 9 hydrophones on the VLA with respect to depth. Note this relation changes according to tidal conditions. Tidal elevation 0900-0930, 30 October is similar to that at 1300 29 October.

The other two measurements were made at remote sites with ranges nominally at 100 m (Fig 5), and 500 m (Fig. 6) from the pile. Precise range depended on deployment conditions and for measurements on October 29th these ranges were 122 m and 502 m, respectively (applying to both Control Pile and Double Wall Pile). For the measurements on October 30th the ranges from the pile source were 135 m and 517 m, applying to the Mandrel Pile tests held that day.

At both remote sites measurements were made with an autonomous recording system (Loggerhead Systems) with hydrophone sensitivity equal to -206 dB re 1 V/μPa, sampling frequency equal to 50000 Hz. The closer (~ 100 m) system was deployed 1 m off the bottom mounted on the tripod as shown in Fig. 7, and the farther (~500 m) system was deployed over-the-side of the work vessel operated by *Citizens for Healthy Bay* at depth 10 m, while the vessel was anchored on site.

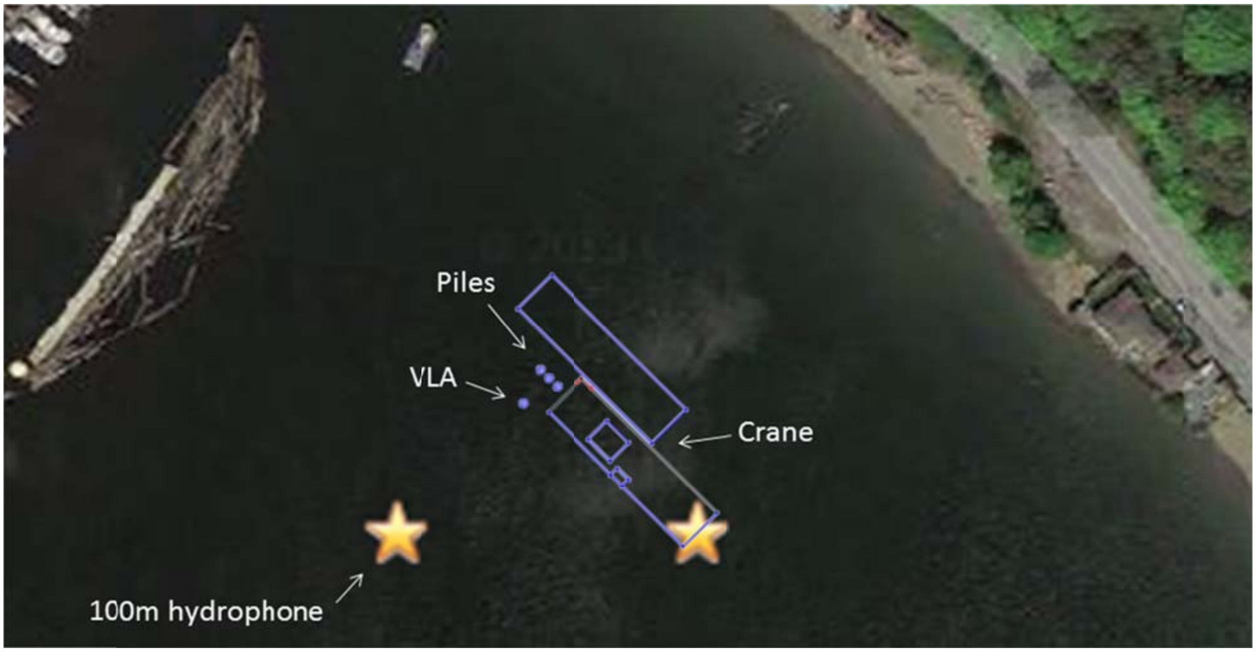


Figure 5. Notional position of the 100 m hydrophone with respect to the pile sources (see text for exact deployment range from piles.)

Figure 6. Notional position of the 500 m hydrophone with respect to the pile sources (see text for exact range from piles.)

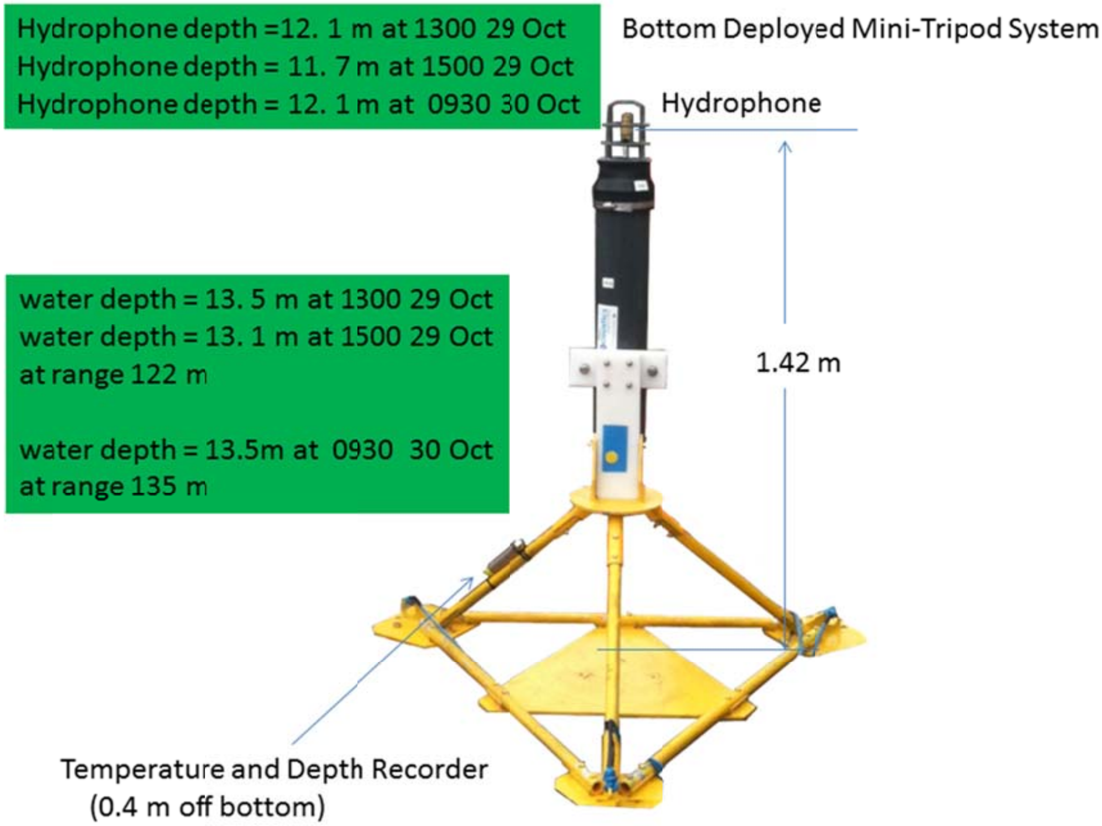


Figure 7. System deployed at notional 100 m range (see text for exact range from piles). Depths for the three key measurements are shown.

A 4th measurement location was used to obtain real-time estimates of underwater sound levels. At this stage of the report, we are forgoing interpretation of measurements from this location because of ambiguities relating to the sound path between pile source and acoustic receiver as shown in Figure 8. This path would have necessarily been under the barge would differ depending on pile test. Furthermore the 3 ft. drop in water level between 1300 and 1500 on October 29th further complicates interpretation because a larger fraction of the water column is blocked.

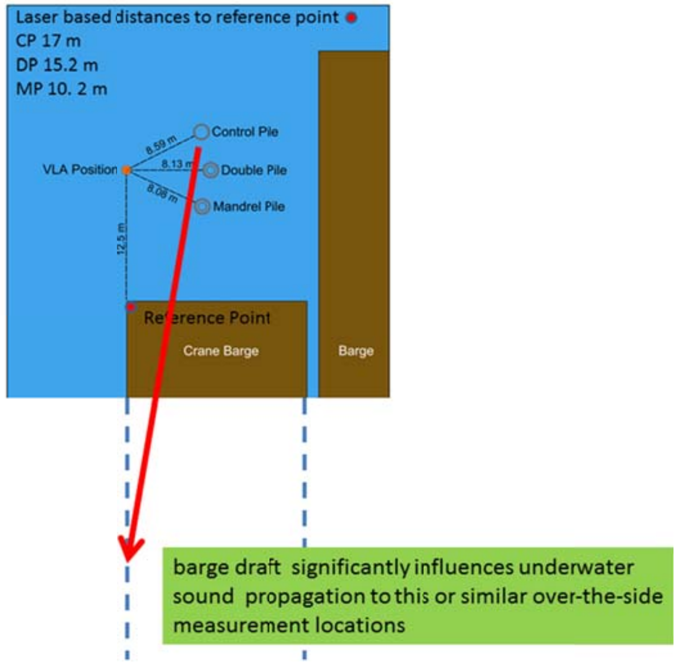


Figure 8. Showing potential issues relating to the underwater sound measurements taken over-the-side of the Crane Barge at the approximate location given by the red arrow head. The crane barge extends beyond the brown-colored area as shown by the dotted lines. The draft of the barge significantly influences underwater sound propagation in the direction of the red arrow. The influence depends on the particular pile under test.

III. General Environmental Conditions and Water Sound Speed

Conditions were generally ideal for the measurements as indicated by calm sea surface conditions shown in Figs. 9a and 9b. Water temperature measured at the bottom at the ~100 m site from the mini-tripod (Fig. 7), and on the VLA (Fig. 4) was 12^{o} C. A sound speed measuring device (YSI) was deployed from the *Citizens for Healthy Bay,* although this was unfortunately not recovered. However based on the temperature recordings and the salinity measurements made in Commencement Bay in 2013, we can estimate sound speed at 1490 m/s.

Figure 9. Photographs: Top (a) looking out from the site and, bottom (b) looking towards the pile source, both documenting the calm sea surface conditions in effect during the measurements.

IV. Basic sequence of Events

For measurement phase 1 on October 29th involving the control pile commencing approximately 12:18 pm, the basic sequence was as follows:

(i) A single "deadblow" defined as impacting the pile with weight of the hammer only, without additional energy supplied to the hammer.
(ii) A series of strikes during which the hammer fuel setting was changed from 1 to 4 (involving settings 1-2-3-4) and bubble curtain activation was either on or off. This series started about 10 min after the deadblow.
(iii) A final series of strikes during which hammer fuel setting was at maximum = 4. This series started about 24 min. after sequence (ii).

The complete record involving the control pile is shown in Fig. 10 (showing just channel 9 for simplicity) with exception of the single "deadblow" that occurred at approximately 12:20 pm. Data from sequence (ii) measured by channel 9 of the VLA is shown in upper figure and sequence (iii) in the lower figure (no strikes occurred within the 2-minute gap of the upper and lower figures.)

At the time of the writing of this draft report, the meta data required to establish the precise actions and their timing during sequence (ii) relating to changes in fuel settings and the bubble curtain, is not available. These changes modulated the peak pressure by approximately 10 dB (e.g., as shown in Fig. 11). Thus, for purposes of comparison between the control pile and the test pile we will only show results from the deadblow and sequence (iii).

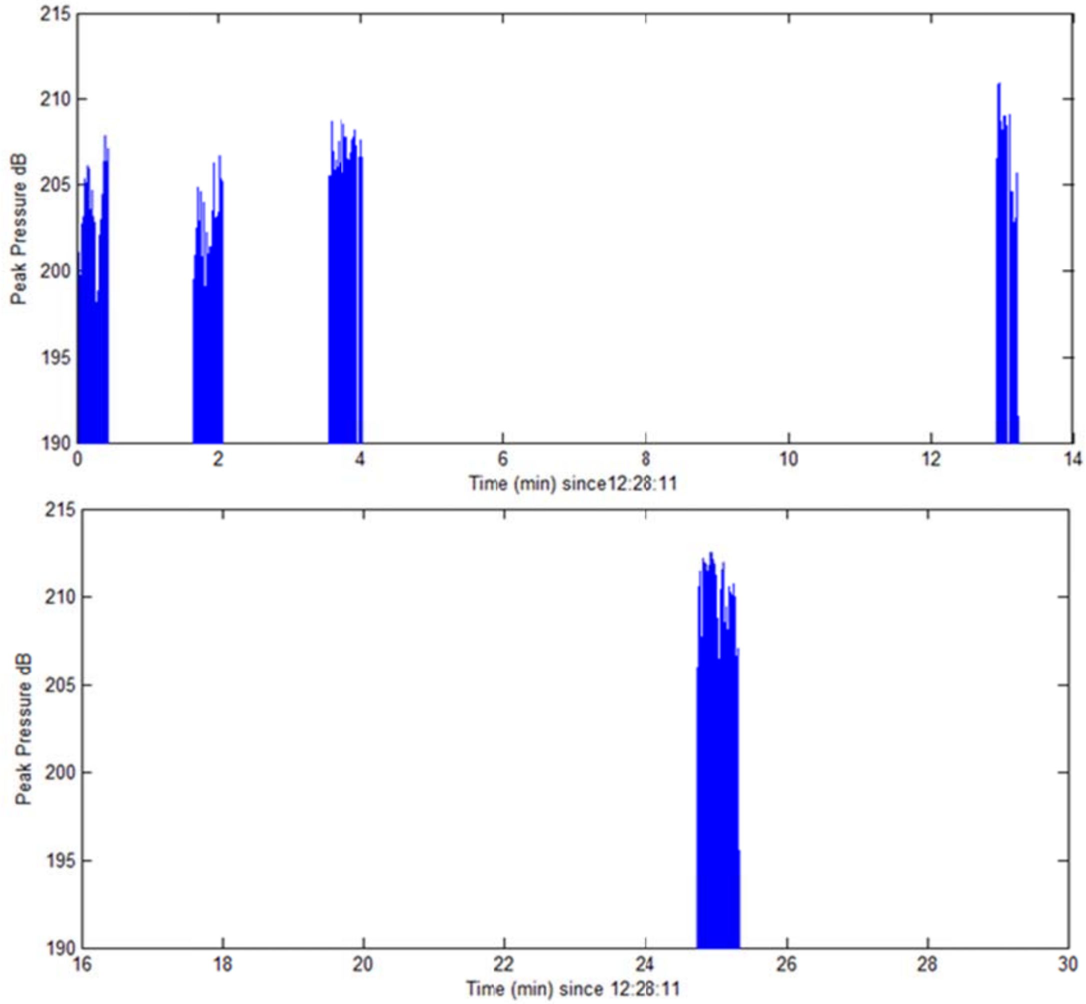


Figure 10. Pressure recording from channel 9 (lowest channel) of the VLA for series of hammer strikes made on the control pile on October 29th. Upper plot shows period during which the hammer fuel setting was changed and/or the bubble curtain was activated and deactivated. Lower plot shows final set of strikes during which the hammer fuel setting was held constant at setting = 4. Data are absolute pressure expressed in dB re 1 μPa.

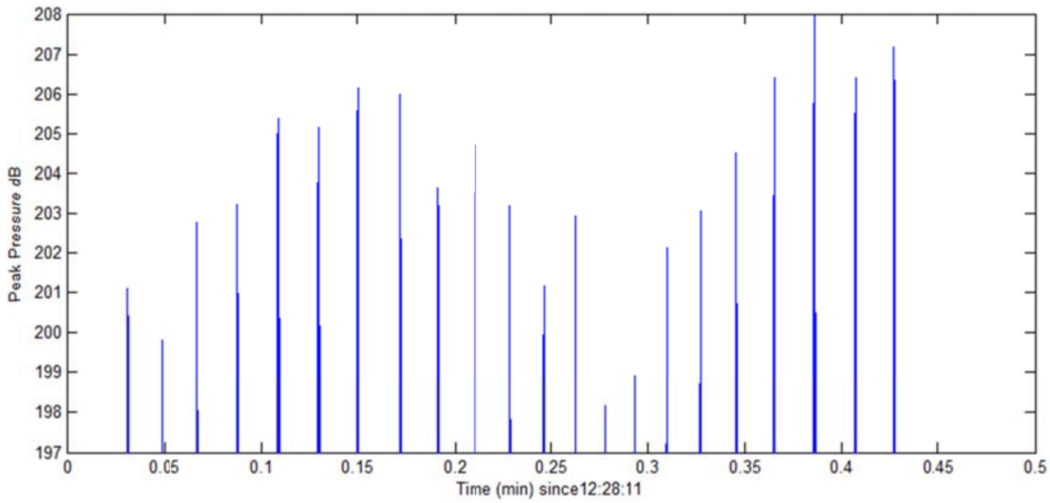


Figure 11. Expanded view of the first 30 sec from Fig. 10 (upper). NOTE: pressure is absolute pressure expressed in dB re 1 μPa, up to 10 dB changes are seen.

For measurement phase 2 on October 29th involving the double wall test pile commencing approximately 14:18 pm, the basic sequence was as follows:

(i) Two “deadblows” defined as impacting the pile with weight of the hammer only, without additional energy supplied to the hammer.

(ii) A series of strikes during which the hammer fuel setting was changed from 1 to 4 (involving settings 1-2-3-4). No bubble curtain was involved. This series started about 3 min after the deadblow.

(iii) A final series of strikes during which hammer fuel setting was at maximum = 4. This series constituted the last portion of series of strikes that started with sequence (ii)

The complete record involving the double wall test pile is shown in Fig. 12. Starting at approximately minute 4 (on the time scale of the figure) fuel settings were changed in an unknown manner and duration causing the modulation shown in yellow shade. The blue shade denotes the period where fuel setting was definitively set to, and held at constant setting = 4, and thus, only this segment of data will be used for comparison between the control pile and the test pile.

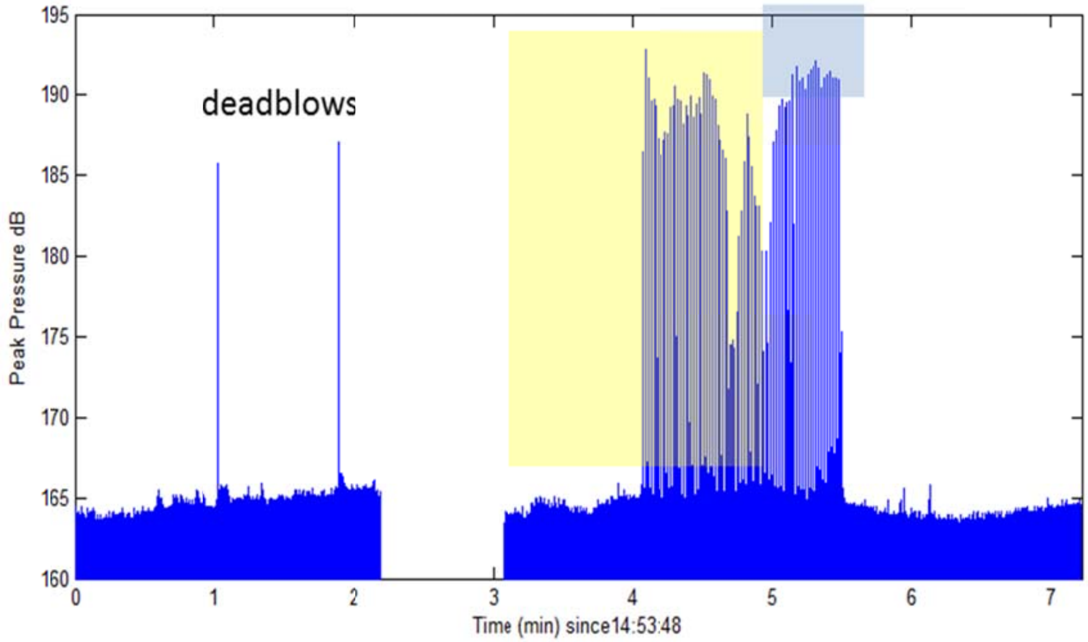


Figure 12. Pressure recording from channel 9 (lowest channel) of the VLA showing all hammer strikes made during double wall pile test on October 29th. (No strikes occurred during the period between approximately 2 and 3 min.) Starting at approximately minute 4 on this scale fuel settings were changed in an unknown manner and duration causing the modulation shown in yellow shade. The blue shade denotes the period where fuel setting was definitively set to, and held at constant setting = 4. NOTE: pressure is absolute pressure expressed in dB re 1 μPa.

For measurement phase 3 on October 30th involving the mandrel test pile commencing approximately 09:16 pm, the basic sequence was as follows:

(i) Three "deadblows" defined as impacting the pile with weight of the hammer only, without additional energy supplied to the hammer.

(ii) A series of strikes during which the hammer fuel setting was changed from 1 to 4 (involving settings 1-2-3-4). No bubble curtain was involved. This series started about 1 min after the deadblows.

(iii) A final series of strikes during which hammer fuel setting was at maximum = 4. This series started about 2 min. after completion of with sequence (ii)

The complete record involving the double wall test pile is shown in Fig. 13. Note in this case we have chosen to show the record as measured at the remote site located 135 m from the pile. The same situation as regards to meta data exists on October 30th, and the changes made during the period denoted by the yellow shade cannot as yet be further interpreted. The blue shade denotes the period where fuel setting was definitively set to, and held at constant setting = 4. Thus, data from three deadblows, and the blue shaded area will be used for comparison between the control pile and the mandrel test pile.

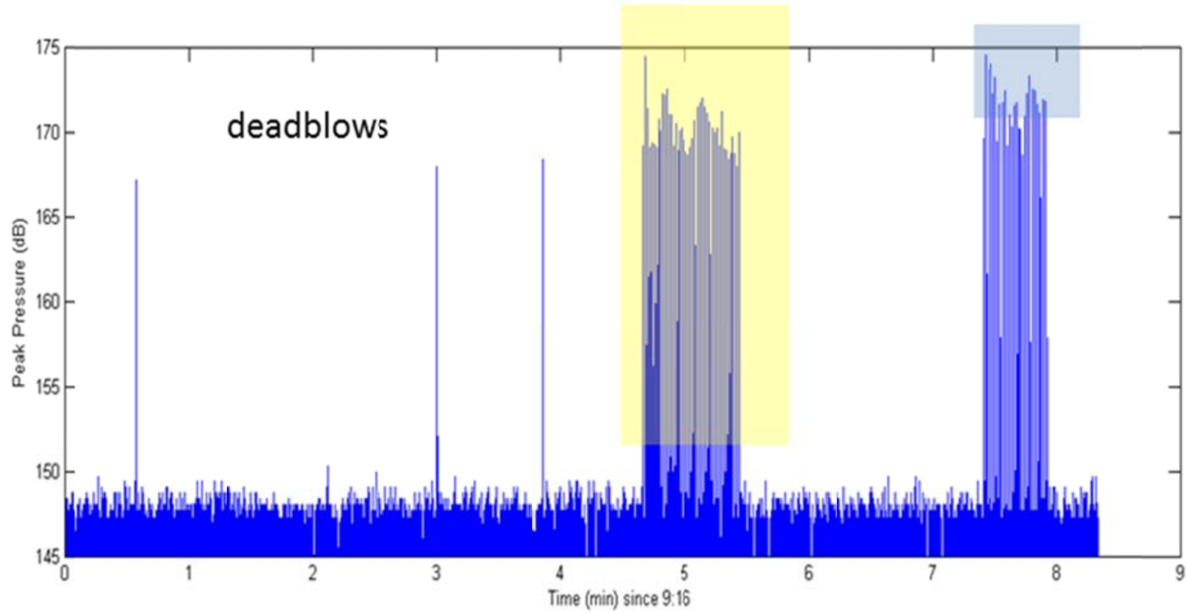


Figure 13. Pressure recording from the autonomous system at range 135 m on all hammer strikes made during mandrel wall pile test on October 30th. Starting at approximately minute 4.5 on this scale fuel settings were changed in an unknown manner and duration causing the modulation shown in yellow shade. The blue shade denotes the period where fuel setting was definitively set to and held at constant setting = 4. NOTE: pressure is absolute pressure expressed in dB re 1 μPa.

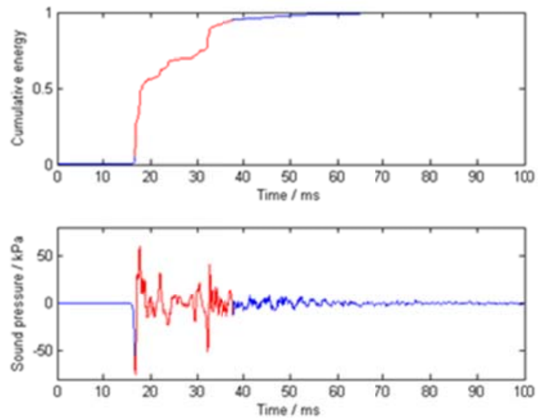
V. Comparisons between the Control and the Test Piles

<u>Comparisons at the Vertical Line Array (VLA)</u>

Three sound metrics are computed from the acoustic measurements for use in comparing the sound fields originating from the control pile and the two test piles. The first is the peak pressure defined as the maximum absolute value of the pressure for a given strike, expressed in dB re 1 μPa. For example, Figs. 10-13 show some "quick look" estimates of this metric.

The remaining two are Sound Exposure Level (SEL) and RMS pressure, defined over the time span corresponding to 90% of the energy of the received pulse as shown in by the red segment in Fig. 14. The RMS pressure and SEL are simply related by the 90% energy time span, and an operation as shown in Fig. 14 is done on every pressure time series associated with pile strike, received on each hydrophone.

Figure 15 examples of PEAK, RMS and SEL as measured on channels 1 and 9 on the VLA, from control pile (left column) and the double wall test pile (right column); these channels chosen to give a representative picture of the shallowest (channel 1) and deepest (channel 9) measurement. The shaded areas in each case denote the section of steady conditions during which the hammer fuel setting equaled 4, and over which averages are made of the metrics comparison. For example, the blue shaded area for the double wall test pile corresponds to the blue shaded area in Fig. 12.



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

Figure 14. Illustrating the definition of the time span corresponding to 90% of the energy of a broad band pulse. The time span, red segment in lower left figure is determined by squaring and integrating the pulse in a cumulative sense (upper left figure) 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.

The key results from the testing on October 29th as measured at the VLA site are shown in Fig. 16. The legend identifies the three metrics with color code. The metrics as a function of depth for individual strikes are shown by thinner lines of the same color, with results from control pile (CP) distinguished from the double wall test pile (DW) by the solid and dashed thick lines, respectively, used to represent the *linear average* (i.e, non-decibel average) of the strike data expressed in decibels.

Note that depths for the CP and DW cases differ for the October 29th owing to the 0.9 m tidal difference between about 1 pm (CP) and 3 pm (DW). The individual strike data from the CP and DW are not comparable, however, the linear averages are comparable. The difference in dB between the CP and DW for each hydrophone, i.e., comparing hydrophone 1 with 1, 9 with 9, etc., is shown by the three columns of 9 numbers each representing in order left to right: SEL, RMS and PEAK.

Of the three metrics, PEAK will typically have the highest variance because it is literally based on one time sample. In contrast, SEL is the most robust measure because of its time-integration property. In terms of the individual strike data we generally observe a higher degree fluctuation in the PEAK data (red) and lower fluctuation in SEL data (blue).

The row of larger numbers at the bottom of the plot is as follows: for RMS and PEAK these numbers are the average of the column of decibel-numbers directly above which are associated with each channel. A true depth-average of PEAK is somewhat ill-defined, and this is also the case for RMS for a transient pulse. However the average values as we have computed them do represent the central tendency of the noise reduction for these metrics.

For SEL the number (17.2 dB) represents the decibel difference of the sum of time integrated squared pressures (Fig. 14), over all channels. This is the most robust estimate of noise reduction as it attempts to capture all the noise energy at least over the 5.6 m span of the VLA.

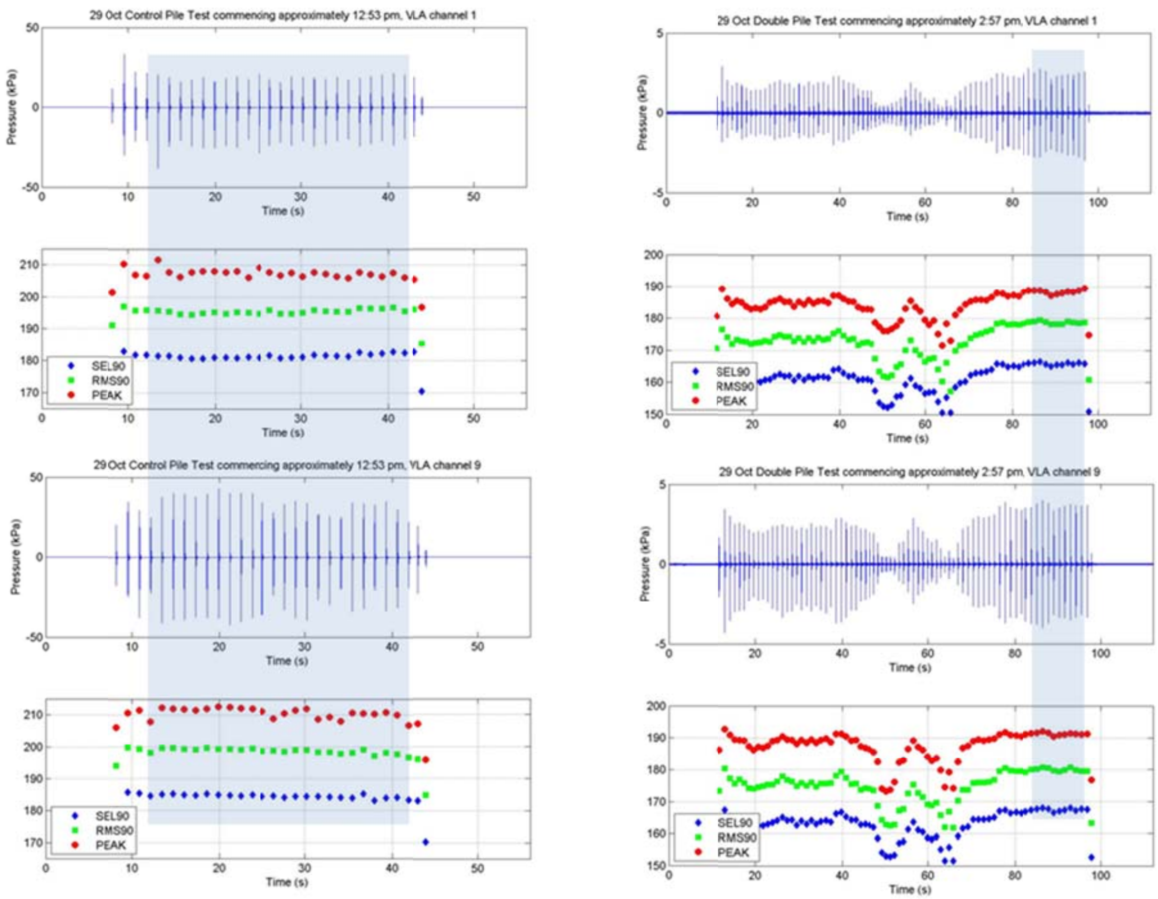


Figure 15. Channels 1 and 9 of the VLA corresponding to the October 29th series of test, with control pile data shown in left column and double wall test pile data shown in right column. The shaded areas in each case denote the section of steady conditions during which the hammer fuel setting equaled 4, and over which averages are made of Peak Pressure, SEL and RMS pressure, for comparison. For example, the blue shaded area for the double wall test pile corresponds to the blue shaded area in Fig. 12. Note the differing time scales that reflect the last sequence of strikes for the control pile and a longer sequence of strikes for the double wall pile with this sequence ending with fuel setting 4.

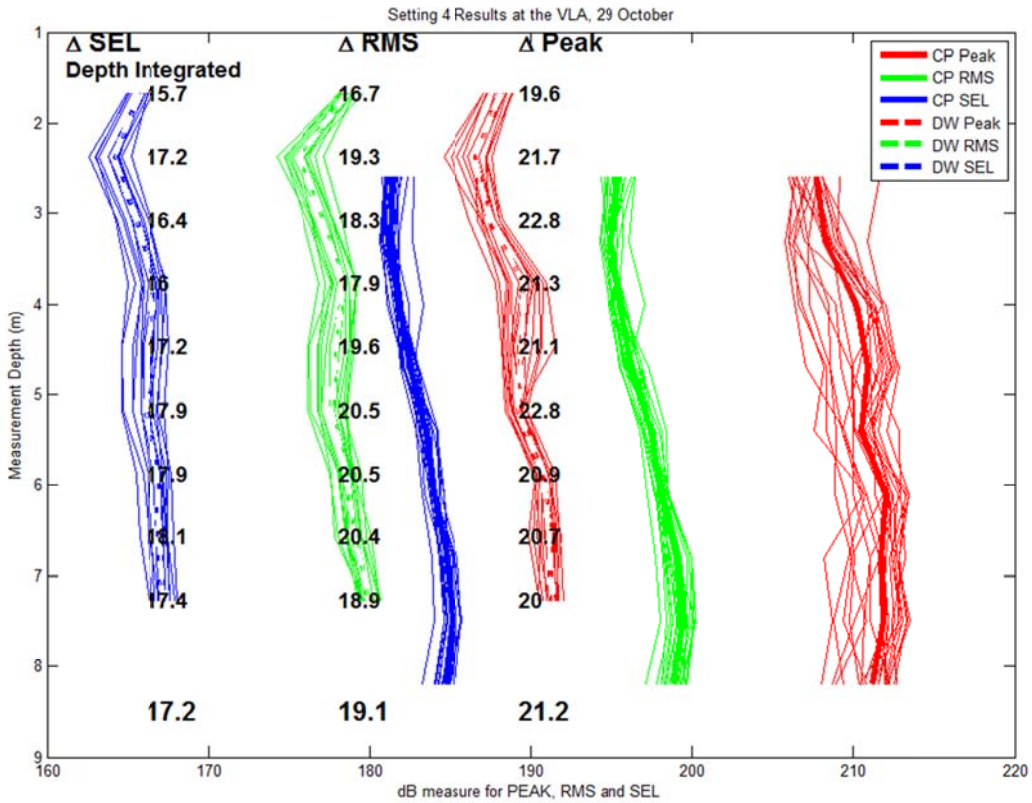


Figure 16. Key results of the fuel-setting-4 tests made on the control pile (CP) and double wall (DW) test pile on October 29th as measured at the VLA. Legend identifies the three metrics and color code with thicker solid line (CP) or dashed line (DW) showing the linear average over the strikes. Individual strike data shown by thinner lines of same color (in some cases hidden by thicker line). The three columns of numbers correspond to the decibel difference in mean value for the 9 hydrophones, with columns going from left to right representing SEL, RMS and PEAK. Bottom row of larger numbers is the depth average of each column for PEAK and RMS. For SEL the bottom number is the difference in depth integrated SEL as discussed in the text.

The VLA results from October 30th testing involving the Mandrel pile are shown in Figs. 17 and 18. As with the double wall test pile, results in terms of estimating noise reduction are compared with the control pile measurements made on October 29th. Figure 17 shows as sample of the strikes measured at the VLA during fuel-setting-4 and Fig. 18 is completely analogous to Fig. 16.

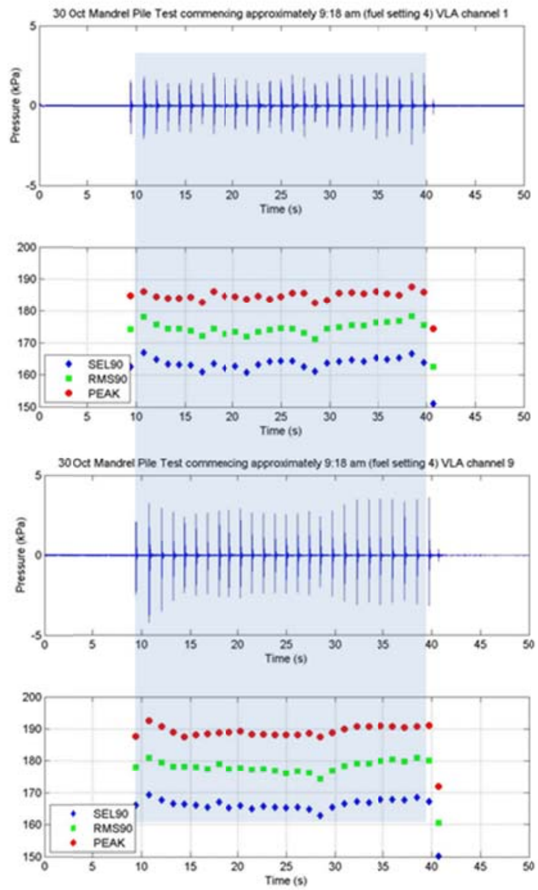


Figure 17. Channels 1 and 9 of the VLA corresponding to the October 30th series of tests involving the mandrel pile. This data is compared with control pile data shown in left column of Fig. 15. Data from shaded areas used in the comparison.

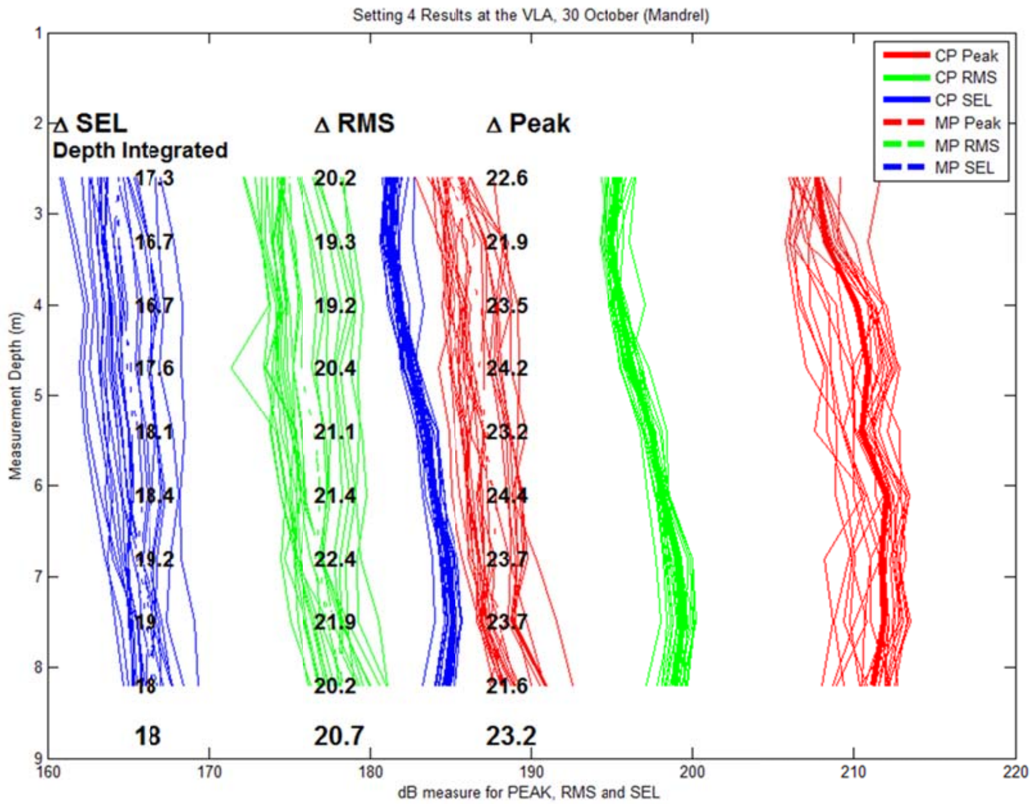


Figure 18. Key results of the fuel-setting-4 tests made on the control pile (CP) and Mandrel test pile (MP) on October 30th as measured at the VLA. Legend identifies the three metrics and color code with thicker solid line (CP) or dashed line (MP) showing the linear average over the strikes. Individual strike data shown by thinner lines of same color (in some cases hidden by thicker line). The three columns of numbers correspond to the decibel difference in mean value for the 9 hydrophones, with columns going from left to right representing SEL, RMS and PEAK. Bottom row of larger numbers is the depth average of each column for PEAK and RMS. For SEL the bottom number is the difference in depth integrated SEL as discussed in the text.

For continuing to the remote measurements it is worthwhile to revisit the two SEL reduction numbers 17.2 dB for the DW and 18.0 dB for the MP. The SEL data from the VLA test are shown below in Fig. 19 where now the horizontal axis is simply hydrophone number. As in Figs. 16 and 18, fluctuations in the individual strikes is evident (though less than the RMS and PEAK metrics). Reasons for the slightly greater degree of fluctuation for the MP tests are possibly associated with leakage in a seal that allowed water to enter the space between the two piles. However both DW and MP settle into similar linear averages over the strikes (black squares.) These averaged data are then summed (in linear space) over the 9 hydrophones to represent a kind of depth-integrated SEL, with the decibel differences shown.

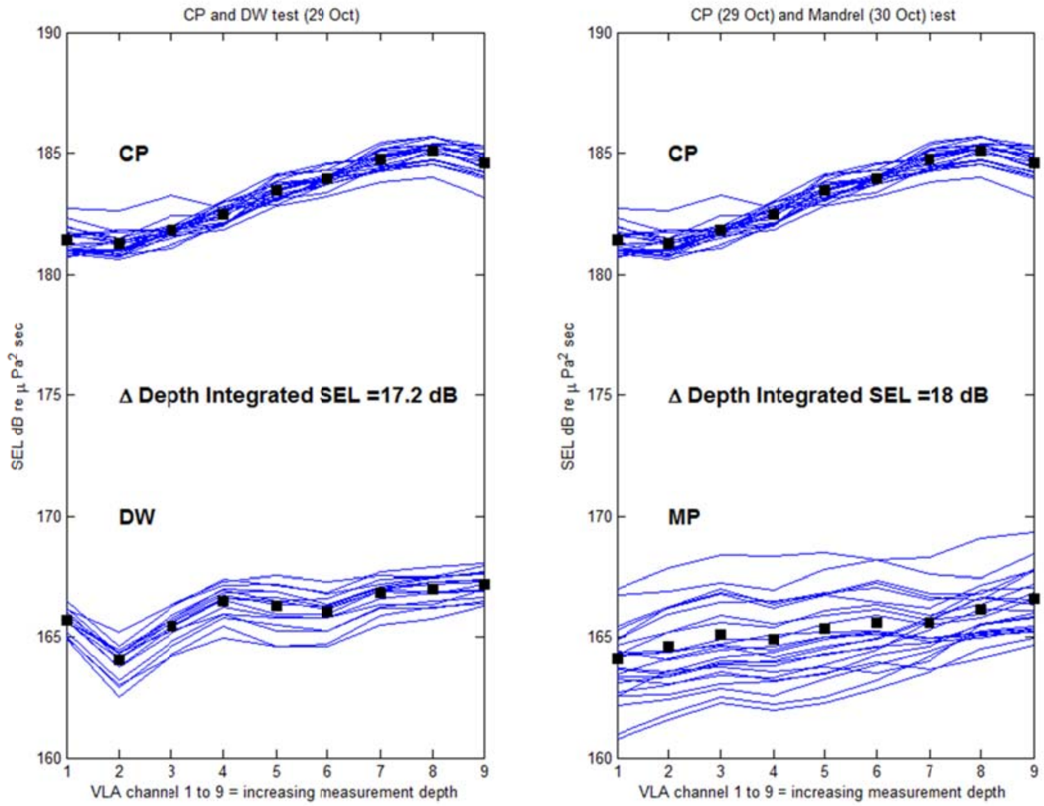


Figure 19. SEL as a function of hydrophone channel for individual strikes (thin blue lines) for the control pile (CP), double wall test pile (DW) and mandrel test pile (MP). Black squares denote the linear average of individual strike SEL for each hydrophone. These data are then summed over all hydrophones (in linear space) with the result decibel difference shown for each test (17. 2 dB for the DW test, and 18 dB for the MP test.

<u>Comparisons at the two remote sites</u>

The results from October 29th testing as measured at the two remote sites are shown in Fig. 20, and from the October 30th testing in Fig. 21.

Here the legend color code also identifies the three metrics. Individual strike data is indicated by asterisks and these correspond one-to-one with those measured at the VLA. The linear averages of the strike data are shown by the closed squares for the control pile (CP) on October 29th, and open squares for the double wall pile (DW) and mandrel pile (MP).

The rows of numbers are the decibel difference in mean values going from left to right: SEL, RMS and Peak, which are measured at range, 122 m (lower row) and 502 m (upper row) for October 29th, and ranges 135 m and 517 m for October 30th.

We observe that the 17.2 dB value for difference in depth integrated SEL at the VLA has reduced to ~14 dB at range 122 m, then increased back to at more consistent 16 dB at range 502 m. The mandrel pile test results, although necessarily compared with control pile test from the day before, are very similar to the double wall pile results insofar as we also observe a ~14 dB at range 135 m, which then increased back to at more consistent 16 dB at range 517 m.

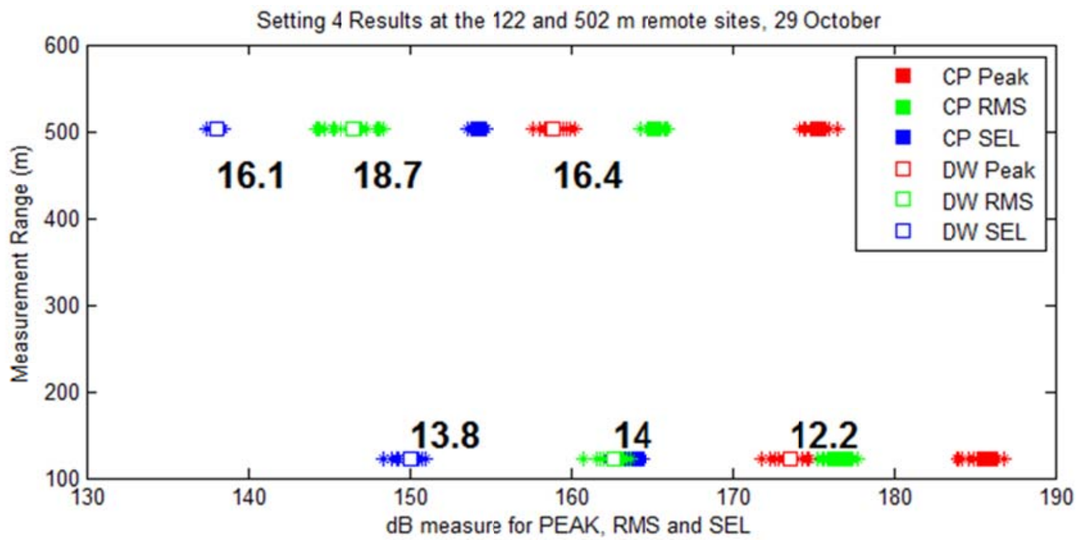


Figure 20. Key results of the fuel-setting-4 tests made on the control pile (CP) and double wall (DW) test pile on October 29th at the two remote sites, range 122 m (1.4 m off the bottom) and range 502 m (10 m measurement depth). Legend identifies the three metrics with closed squares (CP) or open squares (DW) showing the linear average over the strikes. Individual strike data shown by asterisks and which correspond one-to-one with those measured at the VLA. The rows of numbers correspond to the decibel difference in mean values going from left to right: SEL, RMS and Peak, measured at range, 122 m (lower row) and 502 m (upper row).

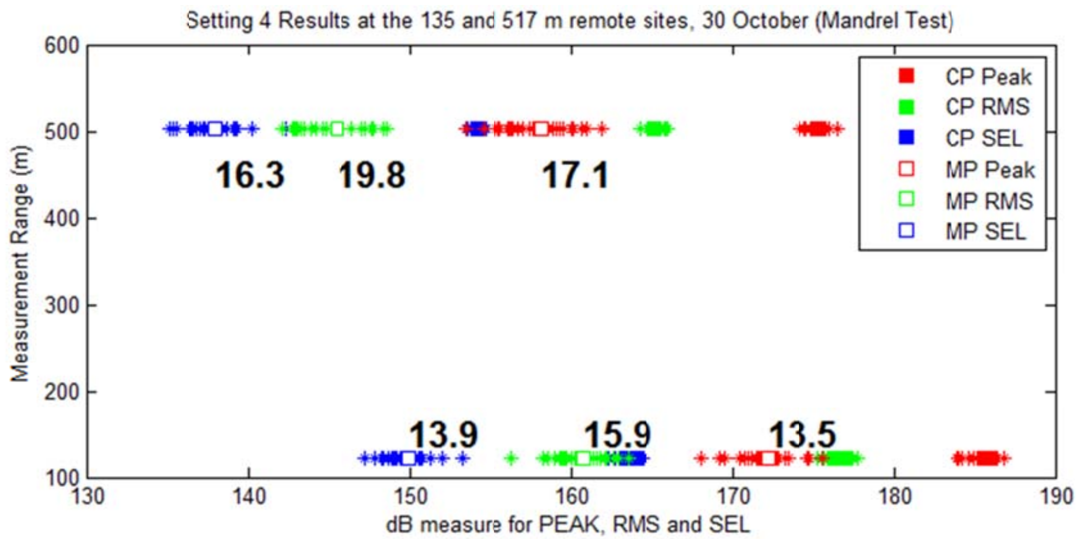


Figure 21. Key results of the fuel-setting-4 tests made on the control pile (CP) and Mandrel test at the two remote sites, range 135m (1.4 m off the bottom) and range 517 m (10 m measurement depth). Legend identifies the three metrics with closed squares (CP) or open squares (MP) showing the linear average over the strikes. Individual strike data shown by asterisks and which correspond one-to-one with those measured at the VLA. The rows of numbers correspond to the decibel difference in mean values going from left to right: SEL, RMS and Peak, measured at range, 135 m (lower row) and 517 m (upper row).

VI. Summary of Underwater Noise Attenuation Results

Table 1 below summarizes the results for underwater noise reduction performance for the SEL, RMS and Peak pressure metrics, for the double wall test pile measured on October 29th (yellow shade) and mandrel test pile measured on October 30th (green shade), where in both cases the reduction is relative to the control pile measurements made on October 29th.

At first glance it may seem curious that for a given metric the performance depends on the range measured. For example, for the double wall test pile measurement made on October 29th, SEL reduction was 17-18 dB at the VLA, decreased to ~14 dB at the 122 m and 135 m sites, and then increased to 16 dB at the 502 m and 535 m sites.

Measurement Range	VLA: 8-8.5 m		Remote 1: 122-135 m		Remote 2: 502-535 m	
SEL Reduction (dB)	17.2	18.0	13.8	13.9	16.1	16.3
RMS Reduction (dB)	19.1	20.7	14.0	15.9	18.7	19.8
PEAK Reduction (dB)	21.2	23.2	12.0	13.5	16.4	17.1

Table 1. Summary of noise reduction in decibels for the SEL, RMS and peak pressure metrics. Yellow shaded values are for double wall test pile (Oct 29th test), and green shaded values are the mandrel pile (Oct 30th test). Slightly different ranges apply to the remote measurements made on October 29th and 30th.

However, the field from impact pile driving is complex and spatially varying. Figure 22 shows a notional field strength of a metric proportional to SEL from impact pile driving, along with the approximate bathymetry for the Tacoma site, and locations of the VLA and two remote measurements. The field is produced using the parabolic wave equation and implementing the phased Mach-wave approach outlined in Reinhall and Dahl[1]. An important characteristic of this field is the spatially-varying field seen reflecting from the surface and bottom and adjusting to the increasing depth. It is anticipated that the acoustic field from a noise-suppressed pile will have less of this characteristic.

Therefore, at some remote measurement locations it is possible to measure a reduced level of sound from impact pile driving, in comparison with the level associated with that from a noise-suppressed pile. Such a location might be in the vicinity of 700 m at depth 10 m, which is one reason we avoided this range. This might have also influenced the measurements at range 122 m (and 135 m).

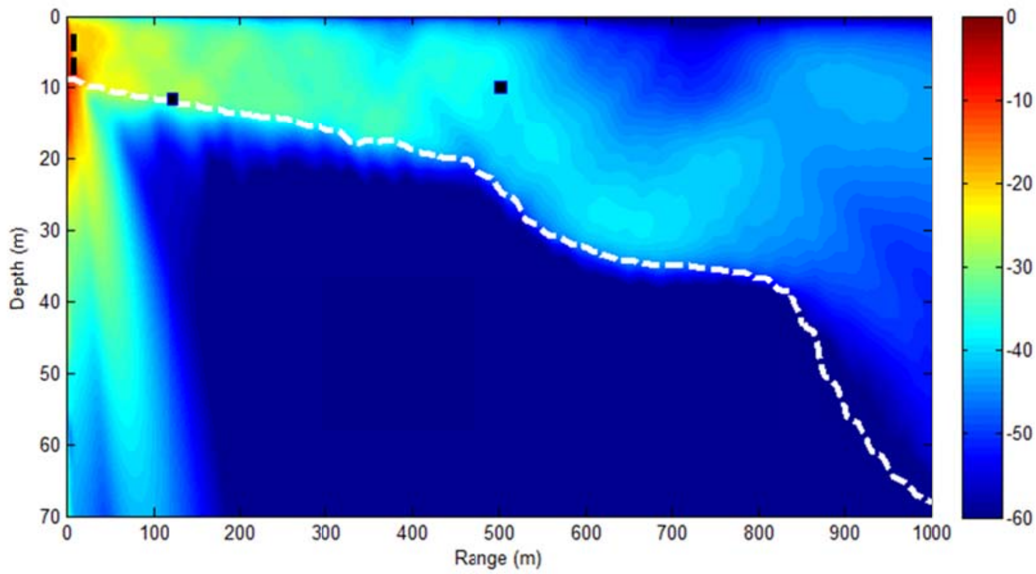


Figure 22. Notional field strength in decibels for SEL (i.e., proportional to) from impact pile driving based approximately bathymetry (white dashed line) for the Tacoma site and tidal conditions in effect at 1300 on October 29th. The black marks show approximate locations of the vertical line array near range 8 m, and the two remote measurements at ranges 122 m and 502 m.

Appendix A: Spectral Content of Sound Exposure Level (SEL)

Figure A1 shows the Sound Exposure Level (SEL) as a function of frequency for measurements made on the VLA (channel 9). The results indicate that the reduction of SEL measured for the two test cases occurred over a broad range of frequencies without necessarily being frequency selective.

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[1] Reinhall, P.G. and P. H. Dahl, "Underwater Mach wave radiation from impact pile driving: Theory and observation', J. Acoust. Soc. Am., 130, Sep. 2011, pp. 1206-1216.

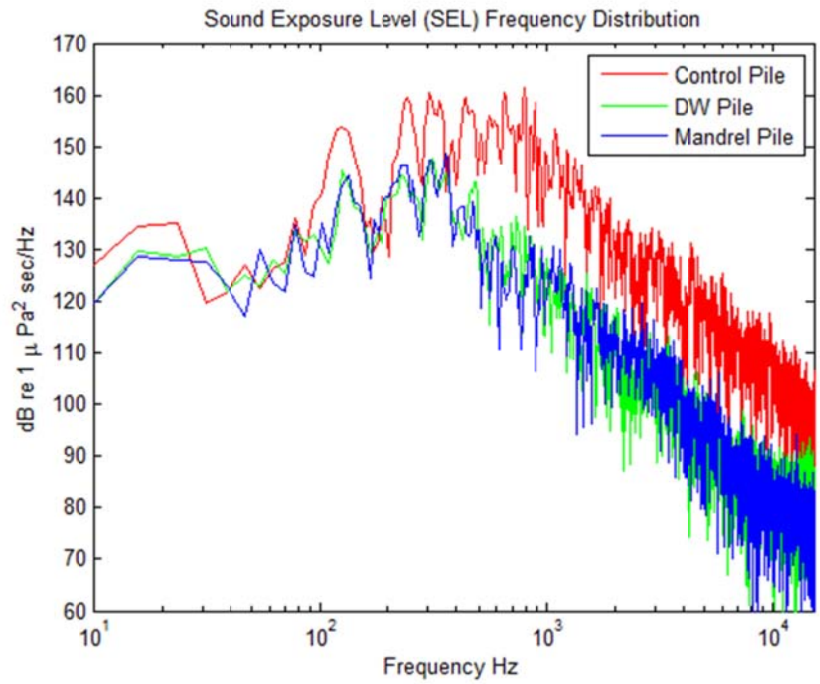

Figure A1. Frequency distribution of SEL for the Control Pile and two test piles.

Appendix B: Cumulative SEL (cSEL) for October 29th and October 30th

On October 29th there was a total of 185 strikes made as part of the Control Pile and the Double Wall Pile testing . At the remote range of 122 m the cSEL is 183 dB re 1 μPa^2 sec, based on computation of the single SELs for all the strikes shown below in Fig. B1. Therefore, the 187 dB cSEL isopleth radius was less than 122 m on October 29th. Based on the modeling shown in Fig. 22 we estimate the range to the 187 dB cSEL isopleth as approximately 60 m.

On October 30th, there was a total of 70 strikes involving the Mandrel pile, which put the cSEL at 168.3 dB re 1 μPa^2 sec at the 135 m remote measurement range. At the VLA site, the typical single SEL on channel 9 was 166 dB (see Fig. 18). Assuming this value applied to all 70 strikes, this puts the cSEL at 184 dB re 1 μPa^2 sec at the VLA range of about 8 m. Therefore the 187 dB cSEL isopleth radius was less than 10 m on October 30th.

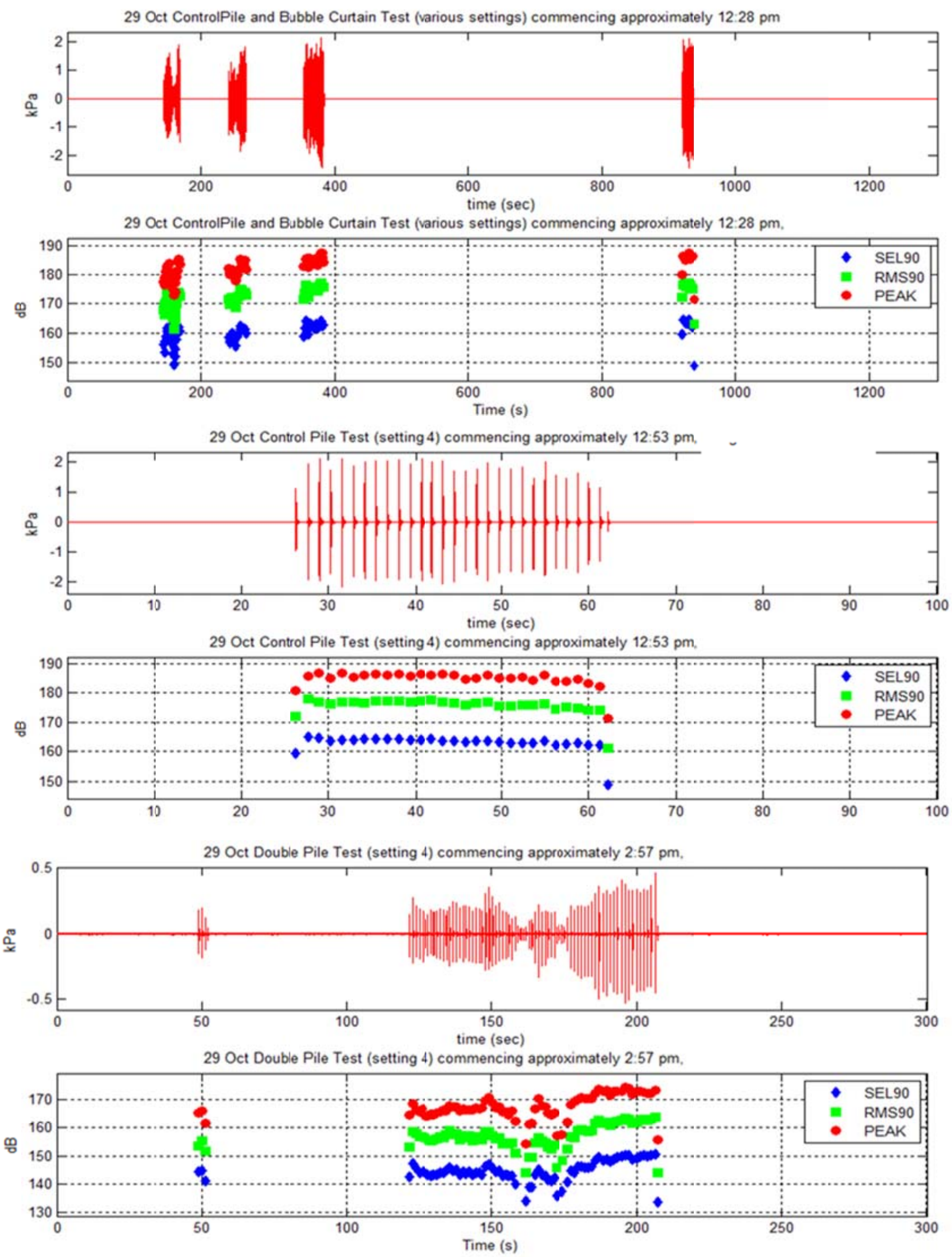

Figure B1. History of all 185 strikes made on October 29th as measured at range 122 m.