APPENDIX H

PROXY SOURCE SOUND LEVELS AND POTENTIAL BUBBLE CURTAIN ATTENUATION FOR ACOUSTIC MODELING OF NEARSHORE MARINE PILE DRIVING AT NAVY INSTALLATIONS IN PUGET SOUND

Proxy Source Sound Levels and Bubble Curtain Attenuation
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Proxy Source Sound Levels and Potential Bubble Curtain Attenuation for Acoustic Modeling of Nearshore Marine Pile Driving at Navy Installations in Puget Sound

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1.0 BACKGROUND

The National Marine Fisheries Service (NMFS) and U.S. Fish and Wildlife Service (USFWS) issue incidental take for Endangered Species Act (ESA)-listed species potentially adversely affected by the Navy's activities. This includes sound pressure levels (SPLs) produced from pile driving. Incidental take statements (ITS) are an outcome of Section 7 consultations and addressed in the Biological Opinions. The NMFS also issues authorizations for noninjurious take (Level B) for marine mammals for noise produced by pile driving. Such take provisions are authorized by the Marine Mammal Protection Act.[1]

ITS often authorize incidental take by the area encompassed within zones above noise thresholds for ESA-listed fish. ITS for other animals such as marbled murrelets and marine mammals are based upon the number of animals anticipated to occur in the zones above the noise thresholds. For example, the peak SPL for the onset of injury threshold for fish is 206 dB referenced to 1 micropascal (μPa)[2]. If actual project noise exceeds the extent of the modeled authorized area, the project would exceed authorized incidental take allotted in the ITS. Consequently, the project would be required to reinitiate consultation under Section 7 of the ESA and a shut-down of impact pile driving would occur until a new ITS is issued. For marbled murrelets and marine mammals, injurious incidental take is avoided by monitoring areas exceeding the injury thresholds. If an animal enters this area, pile driving is shut down until it leaves. In addition, there can be provisions in an ITS or MMPA authorization allocating incidental take for potential behavioral disturbance. In this case, monitoring is required within the behavioral disturbance zones. Therefore, accurate establishment of the extent of the area exceeding established thresholds is essential to complying with the terms of an ITS or MMPA authorization.

When possible data obtained for a given site are used to predict expected source levels. However, for most project sites, prior measurements of the extent of pile driving noise have not been made. For these sites the extents of the areas where noise exceeds threshold values are modeled with an equation for sound propagation using proxy values for the source pile driving levels. Proxy source values are therefore either from prior measurements obtained on-site by installing the same type and size of piles or, when site specific information is lacking, obtained from the same or most similar type and size pile at locations with a similar sound environment. Other important factors include the type of equipment used to install the pile, substrate type, and water depth, all of which result in variations in pile driving noise levels. Detailed analyses of these factors are beyond the scope of this source document. The following section considers the

[1] New NMFS criteria using frequency weighted (filtered) responses are in development, with new standards anticipated. The current revision of this document does not include frequency weighted results; such results will be promulgated in a revised edition.

[2] All peak and root-mean-square (RMS) sound pressure levels in this document are referenced to 1 μPa. All sound exposure levels (SEL) in this document are referenced to 1 μPa^2-second. All peak SPLs in this document refer to absolute peak overpressures or under pressures.

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rationale we used when reviewing proxy impact and vibratory pile driving source values for noise threshold metrics. We first discuss the available data included in the review. Second, we discuss the values for each threshold metric (peak SPL, root-mean-square [RMS], and sound exposure level [SEL]) that will result in a high likelihood of encompassing the extent of actual project noise levels. Last, we review relevant data available for various types and sizes of piles typically used for pile driving and recommend proxy source values for Navy installations in Puget Sound.

Section 2 of this document is a review of attenuation levels reported for various impact pile driving projects.

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2.0 PROXY SOURCE SOUND LEVELS FOR ACOUSTIC MODELING OF NEARSHORE MARINE PILE DRIVING AT NAVY INSTALLATIONS IN PUGET SOUND

2.1 UNDERWATER PILE DRIVING SOURCE LEVELS

2.1.1 Data Sources

Differences in underwater source levels for a given pile size and type will vary because of differences in geologic conditions, water depths where piles are installed, and pile driver type. In other words, the same size pile and type may generate different noise characteristics when installed in dissimilar environments. To obtain source values and model distances to the USFWS and NMFS thresholds for nearshore marine environments at Navy installations in Puget Sound, we reviewed available values from multiple nearshore marine projects obtained from the California Department of Transportation (CALTRANS), Washington State Department of Transportation (WSDOT), and Navy pile driving acoustic reports. Projects were located in California, Oregon, and Washington. Non-marine projects were excluded because of differences in substrate and/or acoustic conditions, and are not relevant herein due to the dissimilar nature from typical work performed at Navy marine facilities in Puget Sound. For example, a project located in Lake Washington and a freshwater bay (SR 520 Test Pile Project) was excluded due to very different substrate conditions present at those sites. Projects located in rivers were excluded because substrate characteristics, such as presence of bedrock, were not typical of Puget Sound. River projects also had different bathymetric profiles as well as increased current velocities. Of the projects reviewed, only measurements from unattenuated piles (e.g. a noise attenuation device was not operating[3]) were evaluated. Attachments 1 through 5 in Appendix A list the projects considered in this review.

All projects considered in the review had similar nearshore project depths from less than 5 m to approximately 15 m with the exception of Test Pile Program at Naval Base (NAVBASE) Kitsap Bangor where depths ranged from approximately 13 to 27 m. Impact pile driver type is listed in the attachments. Impact pile drivers can be drop, pneumatic, hydraulic, or diesel powered. With some exceptions at the Friday Harbor Ferry Terminal, all impact driven piles were installed with diesel powered drivers. Vibratory drivers vary only by size (energy) and type (variable moment/non-variable moment), but because of the limited data set, no attempt was made to distinguish between driver energies when reviewing noise levels produced from different impact or vibratory drivers.

Proxy values in similar marine sound environments can be challenging to obtain for pile driving because of variations in geologic conditions between projects and variability within project sites. Substrate types were not reported for most projects included in the review.

[3] Pile caps are routinely placed on top of piles prior to driving to cushion equipment. While they are recognized as providing some sound attenuation, they are not considered in this analysis because they are part of baseline sound measurement presented in many reports.

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Substrate types typical of Puget Sounds are sand/silt to sand/silt/cobbles overlying glacial till or hard clay layers. Therefore, projects located in the marine waters of Puget Sound, including the San Juan Islands, were considered more heavily because they would be more likely to share the same substrate characteristics than projects located in the San Francisco Bay area, the mouth of the Columbia River, or coastal bays. However, it should be noted that within Puget Sound a considerable variability in substrate conditions can exist between projects and within projects due to harder glacial layers and unforeseen encounters with glacial erratics (e.g. erratic rocks). Depending on the substrate type, piles may easily be advanced or, because of glacial till or submarine boulders, piles may require much more energy to drive. Piles driven to different tip elevations could also experience different driving conditions. For example, fender piles generally are not driven to the same depth as structural piles and may not encounter the same resistance during driving. Therefore, considerable variation in values is expected when looking from project to project or pile to pile within a project. To ensure proxy values are protective of species, conservative values were chosen to encompass regional and pile to pile variation. The following section considers the rationale we used when reviewing values for various sound metrics.

2.1.2 Other Considerations in Evaluation of Pile Driving Source Values

Proxy values need to be conservative. This ensures the area modeled above the injury thresholds is correctly assessed and remains within an ITS for fish. This approach will also preclude incidental take considered injurious based on the established injury criteria of marbled murrelets and marine mammals. In addition, proxy values are used to model the areas above the marbled murrelet and marine mammal behavioral thresholds or guidance values. Sound levels from pile driving are reported on either a per pile basis within a project, or per project summary basis. Summary data reported in acoustic reports varies, but can include one or more of the following:

- Per pile averages
- Ranges
- Minimum and maximum values
- Per project average
- Typical values
- Average range
- Minimum, maximum, average minimum
- Average maximum value
- Standard deviation.

Thus, interpretation of the reported levels may depend on the analytical methodology selected, which in turn can affect the proxy source level selected for modeling analysis. For example, one approach to choosing a source value is to pick the mean value from a number of projects reviewed. The results from the model utilizing this mean value will adequately characterize the estimated average extent of noise from pile driving. However, depending on the pile to pile variability it would only characterize the area for individual piles if the pile to pile variability in the source data were low. If the data were highly variable, the extent of the area above the threshold would be smaller or larger than described by the model on a per pile basis. Therefore, on-site monitoring of pile driving noise could exceed the modeled values on a significant portion of the piles. Another, but more conservative approach is to select the proxy source value from the highest value of all values reported. This method would ensure that most, if not all, measured values on a pile by pile basis would be below the selected value, but could significantly overestimate the area or extent of biological impact.

In the section below we outline the rationale we used for selecting proxy values from the available data for each threshold metric. Values were chosen to ensure that a reasonable worst case scenario is modeled to estimate the extent of noise from pile driving.

2.1.2.1 ROOT MEAN SQUARE

The root-mean-square (RMS) value is the metric used to define the behavioral zones for fish, marbled murrelets, and marine mammals. For piles that are impact driven, RMS values are generally reported for individual piles over the duration of the driving of a given pile; often the number of strikes is also reported on a per-pile basis. Thus, in order to best characterize a broad-base proxy SPL, average RMS pressures were computed from the reported SPL (dB) values, and then weighted by the number of pile strikes for a given pile. This weighting methodology estimates proxy values across multiple projects with differing numbers of piles or strike counts, and the effect of using weighting values ensures that a single project or pile does not overtly bias the result high or low. This proxy value represents the most likely value expected for individual pile strikes for a typical project.

For piles that are vibratory driven, RMS values are typically computed over 10-second or 30-second averaging periods, and represent the most probable typical value over a long event. Thus, recommended proxy RMS values for vibratory and impact pile driving are computed using different techniques. For vibratory piles, reported values were selected on a pile-by-pile basis for a given pile type and size. An average value was computed by converting selected SPL values (dB) into pressure values, summing them together in linear space, dividing by the total number, n, of selected piles, and converting the result back to SPL (dB). In following this approach, the proxy value represents the arithmetic average value for each pile type and size from applicable projects. Thus, for vibratory driven piles averaged RMS values were used from all applicable projects as a representative average level of long-term pile driving events.

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Weighted SPL averages are computed by first converting all SPL values to linear space, weighting pressure values by the number of events (for example, by number of strikes, *n*), normalizing by dividing by the number of events, and then converting back to SPL. Using k as an index counter for all piles, 1 = pile #1, 2 = pile #2, etc.:

$$Weighted\ SPL = 10 \log_{10}[\frac{1}{n_{total}} \sum_{k=1}^{n_{total}} (n_k P_k)]$$

where

$$n_{total} = n_1 + n_2 + n_3 \ldots$$

Charts depicting the behavior of the measured data used to prepare proxy values within this document are presented in Appendix B. Two types of charts are provided. First, for all data types, a sorted chart showing amplitude for all piles included, recommended proxy value, and when available, minimum and maximum levels observed. Next, the cumulative probability distribution function charts are provided for all pile sizes, with the recommended proxy value annotated on each chart.

2.1.2.2 PEAK SOUND PRESSURE LEVEL

The peak sound pressure level (SPL) metric is used to evaluate the potential for injurious effects to fish. The barotrauma injury to fish due to peak over or under pressurization could result in instantaneous injury with a single strike. Average peak impact SPL values were selected from applicable projects, from which a weighted probability distribution function (PDF) was computed based on the number of pile strikes for each pile. To ensure a conservative proxy value, a value representing the ninetieth percentile of the PDF was selected, meaning that for a typical impact pile driving project, 90% of all pile strikes would typically occur below this proxy value. Use of this value ensures potentially injurious effects to fish would have a high likelihood of being within the area exempted for incidental take.

2.1.2.3 SOUND EXPOSURE LEVEL

The sound exposure level (SEL) metric for impact driving is used to calculate the area of cumulative exposure potentially resulting in injury to fish or marbled murrelets over a daylong pile driving event (the accumulation of energy received from all pile strikes). To compute the cumulative SEL all single strike SEL energy in a workday is summed to calculate the overall SEL. However, modeling for the SEL "dosage" generally involves estimation of a typical single pile value logarithmically added to sum the expected energy over the day. While some strikes may be lower and some higher than the mean SEL value, use of the mean value would result in the best overall estimate of expected cumulative energy over the work day. In practice, the SEL value will vary on any given workday due to variability in the levels measured for each individual strike. The acoustic reports reviewed typically provided the mean single strike SEL per pile. Therefore, the most representative estimate of the single strike SEL for a proxy value is to use a mean SEL value from data from all piles in applicable projects. Furthermore, to avoid biasing the data high or low from a single pile or project, a weighted average was computed using the number of pile strikes, *n*, in the same manner as was followed for computation of impact RMS values. This approach ensures that a single project or pile does not bias the result high or low. This proxy value represents the most likely value expected for individual pile strikes for a typical project.

2.1.3 Impact Driving Source Values

Table 2-1 summarizes projects from Attachment 1 in Appendix A that were considered in the final analysis and highlights proxy values. Theses highlighted proxy source values are reasonably conservative for modeling future Navy pile driving projects in Puget Sound. Detailed discussions of the projects considered and the values obtained for each pile type and size are provided below.

Table 2-1. Summary of Unattenuated Impact Pile Driving Levels Considered. Recommended Proxy Source SPLs at 10 m Bolded.

Pile Size	Number of Projects Considered[1]	Range of Average RMS (n-weighted pile average) dB re 1μPa	Range of Average Peak (90% PDF value) dB re 1μPa	Range of Average SEL (n-weighted pile average) dB re 1μPa
Steel				
24-inch	2	181-198 (**193**)	196-213 (**210**)	176-185 (**181**)
30-inch	3	192-196 (**195**)	203-217 (**216**)	182-187 (**186**)
36-inch (all projects)	3	185-196 (**192**)	202-211 (**211**)	173-186 (**184**)
36-inch (Bangor only)	1	185-196 (**194**)	Not reported[3]	173-183 (**181**)
All 24/30/36-inch	7	181-198 (**193**)	196-217 (**211**)	173-193 (**184**)
Concrete				
≤18-inch	3	158-173 (**170**)[2]	172-188 (**184**)[2]	147-163 (**159**)[2]
24-inch	7	167-179 (**174**)[2]	180-191 (**188**)[2]	158-167 (**164**)[2]

[1]See Appendix A, Attachment 1 and 2 for projects reviewed.
[2]Number of pile strikes, *n*, was not available for any concrete projects; all piles were equally weighted.
[3]Although absolute peak values were collected for TPP testing, average peak values were not reported; unattenuated data from EHW-2 was not collected.

2.1.3.1 24-INCH STEEL PILE IMPACT DRIVING SOURCE VALUES

Attachment 1 in Appendix A lists six marine nearshore projects reviewed for possible inclusion in the analysis. Data for one 24-inch pile installed with an impact hammer in the Test Pile Project at NBK Bangor are listed in Attachment 1. However, only 7 pile strikes were reported and measurements from this pile are lower than all of the other five projects reviewed. Therefore, these data were not considered in the selection of the most conservative value. Of the remaining five projects reviewed, the Bainbridge Island Ferry Terminal Preservation Project and the Friday Harbor Restoration Ferry Terminal project were considered as the most representative of typical glacial till and erratics encountered in Puget Sound and were carried forward in the analysis. We based this on the assumption that substrate conditions are more similar than those found in San Francisco Bay or the mouth of the Columbia River.

For the two ferry terminal sites, five piles were driven at Bainbridge Island in substrate that consisted of a mix of sand and fist-sized rocks with occasional rocks one-foot in diameter. At Friday Harbor six piles were driven into a silty sand substrate approximately 9 meters thick and underlain by a hard clay lens. Three of the piles at this site encountered a large rock ledge approximately 10.7 meters below the mudline. One of the six piles in the project had the high end of the data clipped[4] and therefore invalid, so this pile was excluded from the analysis. This project used different hammer types, but because the report noted little variation in the data, all five remaining piles were included in our review. Data from the two ferry projects only included values without a bubble curtain attenuator operating, i.e. no attenuation.

Source levels for each metric reviewed are discussed below. Table 2-1 summarizes unattenuated impact pile driving source data from Attachment 1 for the two ferry terminal projects.

RMS SPL

Weighted average proxy RMS source values for the two Puget Sound ferry terminal projects were 189 dB (range 181 dB to 193 dB) and 195 dB (range 193 dB to 198 dB) (Attachment 1), representing 1007 pile strikes. Therefore, actual RMS values would be expected to fall between 181 dB and 198 dB. The weighted average RMS value of 193 dB was chosen as a conservative value that likely encompasses the average extent of the area exceeding the injury thresholds for marine mammals and the behavioral thresholds for marine mammals, fish and marbled murrelets.

Peak SPL

Average peak SPLs reported for individual piles at the Bainbridge Island and Friday Harbor projects were 202 dB to 209 dB and 196 dB to 213 dB, with an average weighted value of 207 dB. Of the applicable projects, the 90% probability from the weighted cumulative distribution density function value of 210 dB was chosen as a conservative proxy value that likely encompasses the modeled extent of the area over the onset of injury threshold for fish. Table 2-1 summarizes the values from the two projects considered likely to be most representative.

SEL

Mean weighted SEL values for the two Puget Sound projects reviewed are each 181 dB for all piles. The mean SEL per any one pile for both projects ranged from 176 and 185 dB. These

[4] Clipping occurs when a signal exceeds the linear limits of an electronics system in essence the extreme levels of the signal are truncated or "clipped" off. For pile driving measurements, clipped data can produce results that are lower than the actual signal of interest, thus producing invalid results.

values are higher than the values reported for the other three projects reviewed (project SEL means that ranged from 168 to 177 dB). Therefore, the Washington projects were considered the most conservative and a mean weighted SEL of 181 dB was chosen as a reasonable proxy value of the overall SEL for 24-inch piles.

2.1.3.2 30-INCH STEEL PILE IMPACT DRIVING SOURCE VALUES

Data for 30-inch steel pipe piles were available from three marine pile driving projects in Puget Sound, Washington and one project from San Francisco Bay, California. No projects from Bangor were available for analysis, and data from the California project provided only typical data, and did not provide per-pile SPL or number of strikes for each pile (see Attachment 1 in Appendix A). All available data in Attachment 1 were reviewed. However, as with the 24-inch pile source values, values from the Puget Sound projects were considered the most representative of source values because of similar substrate characteristics and are the only values considered in the Table 2-1 summary. Note that data from the Vashon Island project were acquired from 7m to 16m from the pile, and were normalized using a $15 \cdot \log_{10}$(range/10m) relationship.

RMS SPL

Average RMS source values for three Puget Sound projects ranged from 192 dB to 196 dB. The minimum average value reported for any one pile is 192 dB (Eagle Harbor Ferry Terminal) and a maximum average reported of 196 dB (Vashon Island Ferry Terminal, two piles). The RMS values from three Puget Sound projects were moderately higher than values measured from the California project considered, which reported a typical RMS value 190 dB. A conservative proxy RMS value is the weighted average value of 195 dB from the three projects in Puget Sound representing 263 pile strikes. This value would be a reasonable worst case ensuring that noise levels modeled would have a high likelihood of not exceeding this value.

Peak SPL

Average peak SPLs reported from the Puget Sound projects with available data ranged from 203 dB to 217 dB (n=3 projects) on a per-pile basis, with a computed weighted average of 214 dB. Levels from three piles at Eagle Harbor Ferry Terminal range from 7 to 11 dB quieter than those measured at two other Puget Sound sites, indicating a significant variability between sites. The typical peak SPL reported for the single California project was 205 dB, which was noted to be on the lower end of the range of data reported from Puget Sound, although the number of pile strikes was not reported, thus this data were not included in the weighted average for 30” peak values. The 90% weighted cumulative probability value of 216 dB was chosen as a reasonable and conservative proxy value.

SEL

Average per-pile SEL values were reported for the two Puget Sound Projects representing 214 pile strikes; the Eagle Harbor project did not report single strike SEL levels, and a California project did not report any SEL levels. SEL values from the two applicable projects ranged from

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182 dB to 187 dB with an overall weighted average of 186 dB. Thus, a reasonable conservative SEL source value for future projects in Puget Sound is 186 dB derived from the weighted value of reported Puget Sound levels.

2.1.3.3 36-INCH STEEL PILE IMPACT DRIVING SOURCE VALUES

Data for 36-inch steel pipe piles were available from three marine pile driving projects in Puget Sound, Washington and one project from Humboldt Bay along the California coast (Attachment 1 in Appendix A). All projects installed piles with a diesel hammer. The Humboldt Bay project did not report number of pile-strikes, and furthermore, this pile was only measured by re-striking a pile that had already been driven. Therefore, this project was excluded from the 36-inch average value computations. Data from two piles measured during the NBK Bangor Test Pile Program were at 11m and 20m from the pile, and were normalized using a $15 \cdot \log_{10}$(range/10m) relationship.

RMS SPL

Average RMS source values for the three Puget Sound projects ranged from 185 dB to 196 dB, representing 662 pile strikes, the full range of which were observed during the Test Pile Program at NBK Bangor project. The weighted average value for these projects was 192 dB, and represents a reasonable proxy RMS value for impact driven 36-inch piles. The average RMS value of 193 dB reported for the 36-inch pile from the Humboldt Bay Bridge project in California fell within the range of values for the three Washington 36-inch pile projects reviewed, although as previously discussed, this value was not included in the averaging calculations. Considering just the Test Pile Program at Bangor, 121 pile strikes produced a set of measurements ranging from 185 to 196 dB, with a weighted average value of 194 dB.

Peak SPL

Average peak SPLs reported from two Puget Sound projects ranged from 202 dB to 211 dB on a per-pile basis, representing 541 pile strikes. Average peak values were not reported for the NBK Bangor project. A proxy peak value of 211 dB was chosen representing the 90% cumulative probability SPL.

SEL

Average SEL values were reported for three Puget Sound projects, with 662 pile strikes measured. SEL values ranged from 173 dB to 186 dB with an overall weighted average of 184 dB, the recommended proxy value for piles driven in Puget Sound. Only one value was reported for the Humboldt Bay project, 183 dB, which was within the range of values reported in Puget Sound. A reasonable conservative SEL source value for future projects in Puget Sound is 184 dB derived from the weighted average of three Puget Sound projects. Analyzing data from just the NBK Bangor project resulted in a weighted average value of 181 dB, with a data range of 173 to 183 dB.

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2.1.3.4 COMBINED STEEL PIPE IMPACT DRIVING SOURCE VALUES

Review of RMS, average peak, and SEL values for steel pipe piles of 24, 30, and 36-inches shows that often only slight differences are noted across the three sizes (see Table 2-1). In some cases, weighted average values for smaller piles are higher than for larger piles, even if by only one or two decibels. For this reason a combined analysis was done for each of the metrics to investigate the potential value of preparing overall average values over multiple sizes of steel pipe piles. Each of the metrics is discussed in the following paragraphs.

RMS SPL

Average RMS values over 24, 30, and 36-inch piles ranged from 181 dB to 198 dB, although weighted averages were very close, 193, 195, and 192 dB, respectively, with an overall weighted average value of 193 dB. 30-inch piles (three projects located in Puget Sound, not including any NBK Bangor projects) produced average RMS levels of 195 dB, higher than both 24-inch and 36-inch average values. Even though few piles and a lower number of pile strikes were measured with 30-inch piles, the scatter in the points measured only ranged from 192 to 196 dB, without a large deviation. 24-inch and 36-inch piles have larger data sets, but nonetheless, the recommended proxy value for each of these sizes is only a few decibels different. Figure B-4 in Appendix B graphically shows how the scatter for each pile size compares with other pile sizes. While it is reasonable to assert that RMS impact values for steel pipe piles can be represented by a single, composite value of 193 dB, additional data is recommended to be collected to increase the size of the analysis sample set.

Peak SPL

Peak SPL values varied over a broader range than RMS values, although 24- and 36-inch 90% cumulative probability results were within 1 dB, representing 1,669 pile strikes. 30-inch results were measurably higher than either 24- or 36-inch data, represented by fewer piles, and fewer strikes (263 strikes). Furthermore, 30-inch pile data is somewhat bi-modal in behavior, with three values near 203 to 204 dB, and four in the 211 to 217 dB range, and nothing in between. Figure B-11 in Appendix B graphically shows the distribution of levels by pile size. Three piles represented in the 211 to 217 dB range were measured from distances other than the standard 10 meter de facto measurement range, which were corrected using the traditional practical spreading model. Although not necessarily incorrect, this serves to increase the uncertainty of those measurements. Since none of the 30-inch (nor 24-inch measurements) represent data acquired directly from NBK projects, it makes sense to prepare a broader analysis to consider different pile sizes for the purpose of increasing confidence in the estimated peak values. The 90% cumulative distribution value for all 24-, 30-, and 36-inch applicable projects is 211 dB, represented by 1,932 pile strikes, and is the recommended proxy value for NBK Bangor projects, especially those using 24-inch and 30-inch steel pipe piles, until such time that Bangor-specific data can be acquired using these pile sizes.

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SEL

Weighted average SEL values for 24-, 30-, and 36-inch piles also resulted in somewhat anomalous data with 30-inch steel pipe piles, with both 24-inch and 36-inch data producing lower values. As described above, the 30-inch data set includes range corrected values, and furthermore, only represented 4 piles, since single strike SEL values were not reported for one of the Puget Sound projects (Eagle Harbor Ferry Terminal). Figure B-16 in Appendix B shows the data grouping by pile size. This gives rise to increased uncertainty in the 30-inch average vales.

There is some evidence that SEL values for 36-inch piles at NBK Bangor (182 dB, weighted average) is lower than a proxy value including Puget Sound projects (184 dB). This conclusion is drawn from a modest sample size (4 piles, 121 strikes) of NBK Bangor measurements. Similar analyses could not be done with 24- and 30-inch piles, since these data did not exist for NBK Bangor projects.

Taken in summary, there is motivation to compute a single proxy value for all 24-, 30-, and 36-inch steel pipe piles, but this approach is not recommended at this time due to the uncertainty in the data scatter, and different results among RMS, SEL, and peak metrics. Additional data should be collected before using combined analyses.

2.1.3.5 18-INCH CONCRETE PILE IMPACT DRIVING SOURCE VALUES

Attachment 2 in Appendix A lists three marine nearshore projects that monitored sound levels during installation of 18-inch or similar (16-inch) concrete piles, none of which were conducted in Puget Sound. Two projects were conducted at the Berkeley Marina in San Francisco Bay, California, one in 2007 and one in 2009 using 18-inch concrete piles. Acoustic measurements were only collected for four piles total for both projects. Water depth was fairly shallow ranging from 3 to 4 meters. Source levels for each metric reviewed are discussed below. Another project located near Concord, CA at the Naval Weapons Station (NWS) drove five 16-inch concrete piles, with water depth of 10 meters. Source values for this project were similar to those for the Berkeley Marina projects, and thus data from the Concord NWS were included in the analysis. Table 2-1 summarizes unattenuated impact pile driving source data from Attachment 2 and highlights recommended proxy source values. Since the number of pile strikes for all concrete projects were not reported, pile averages were computed.

RMS SPLs

Average RMS values for three projects using 16 or 18-inch concrete piles ranged from of 158-173 dB (Table 2-1), with an average RMS value of 170 dB over 9 piles, selected as a conservative value likely to encompass the maximum extent of the area exceeding the behavioral thresholds and guidance for marine mammals, fish and marbled murrelets. No concrete pile levels exceed the RMS injury thresholds established for marine mammals (180 dB RMS for cetaceans and 190 dB RMS for pinnipeds).

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Peak SPLs

Average peak SPLs reported for all piles at the Berkeley Marina projects ranged from 172 dB to 188 dB. Because only three projects with relatively small samples sizes were available for review, a per-pile average value of 184 dB was chosen as the recommended SPL proxy value for all piles. This value is below the threshold for the onset of injury in fish (206 dB). Table 2-1 summarizes the values from these projects.

SEL

Two average SEL values of 155 and 159 dB were reported for the two Berkeley marina projects, both with very small sample sets ranging from 147 dB to 163 dB. SEL data were not acquired for the Concord NWS project. The per-pile average value of 159 dB SEL was selected as the most conservative proxy value available for 18-inch concrete piles until additional data are obtained.

2.1.3.6 24-INCH CONCRETE PILE IMPACT DRIVING SOURCE VALUES

Only one value from a single 24-inch concrete pile was available for the Mukilteo Ferry Terminal in Puget Sound. Therefore, we reviewed seven additional marine projects: six in San Francisco Bay, California, and one in Humboldt Bay, California (Attachment 2 in Appendix A). Note that some of the San Francisco Bay projects included data from the same site in two different time periods. Two projects (Humboldt State Floating Dock and Pier 40 Marina) included piles that were driven using a jetting technique, often in combination with a reduced level of fuel to minimize driving energy. Piles driven under these circumstances were not included in the calculation of piles averages. Table 2-1 summarizes unattenuated impact pile driving source data from Attachment 2 and highlights recommended proxy source values.

RMS SPLs

The one pile in Puget Sound reported a maximum RMS value of 170 dB, with average values reported for the California projects ranging from 167 dB RMS to 179 dB RMS. The recommended proxy source value was chosen from the highest average pile value over all projects, 174 dB RMS (Table 2-1). No concrete pile noise levels exceed the RMS injury threshold established for pinnipeds (190 dB RMS), nor the RMS injury threshold for cetaceans (180 dB RMS).

Peak SPLs

Average Peak SPLs reported for projects ranged from approximately 180 dB to 191 dB. The per-pile 90% cumulative probability value of 188 dB was chosen as the recommended proxy peak SPL value. This value is below the peak threshold for the onset of injury in fish (206 dB). Table 2-1 summarizes the values from the two projects.

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Sound exposure levels were only reported for six of the eight projects reviewed, with per-pile values ranging from 158 dB to 167 dB (Table 2-1). The pile SEL average over all projects of 164 dB was considered representative of a conservative average SEL source value for 24-inch piles.

2.1.4 Vibratory Pile Driving Source Values

NMFS has established non-impulsive injury thresholds (180 dB RMS for cetaceans, 190 dB RMS for pinnipeds) and a disturbance threshold (120 dB RMS) for marine mammals. Vibratory driving is considered a non-impulsive sound source. Attachment 3 in Appendix A contains a list of vibratory projects and derived proxy source values we reviewed in order to calculate how far sound from vibratory driving exceeds the thresholds discussed in Section 1.2.1. Table 2-2 presents the summary of vibratory pile driving data from the projects reviewed. Due to the similarity in levels across multiple projects, 16-inch and 24-inch piles were considered together, and 30-inch and 36-inch piles were considered together.

Table 2-2. Vibratory Pile Driving SPLs.*
Recommended Proxy Source SPLs at 10 m Bolded.

Pile Size and Type	Number of Projects Considered[1]	Range of Average RMS dB re 1µPa @ 10 meters	Reasonable Source Level dB re 1µPa dB @ 10 meters
Timber			
12-inch	1	152-155[2]	**153[2]**
Steel Pipe			
16-inch and 24-inch	4	Bangor 153-162 All projects 159-162	**161**
30-inch and 36-inch	7	Bangor 166 All projects 159-172	**NBK Bangor 166** **Other Puget Sound Locations 167**
Steel Sheet			
24-inch	3	160-163**	**163**

[1]See Attachment 3 for projects reviewed.
[2]Data reported at 16m, converted to equivalent range of 10m using 15Log$_{10}$[16/10] range correction factor.
* Recommended values for 10 meters unless otherwise indicated.
**Highest value for pile; value includes some averages from only top or bottom depth measurements and one from top and bottom averaged.

2.1.4.1 TIMBER PILE VIBRATORY DRIVING SOURCE VALUES

Only one timber pile study is available and only for noise measurements taken during extraction of one 12-inch diameter pile (see Attachment 3 in Appendix A). The highest RMS value was 152 dB measured at 16 meters (Table 2-2), with an average value of 150 dB reported at 16 meters.

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2.1.4.2 24-INCH DIAMETER STEEL PIPE PILE VIBRATORY DRIVING SOURCE VALUES

Two projects in Washington and one in California were reviewed for 24-inch diameter steel pipe piles. The Washington marine projects at the Friday Harbor Terminal and NBK, Bangor waterfront, only measured one pile each, but reported similar sound levels of 162 dB RMS and 159 dB RMS (range 157 dB to 160 dB), respectively (see Attachment 3 in Appendix A). Because only two piles were measured in Washington, the California project was also included in the analysis. The California project was located in a coastal bay and reported a "typical" value of 160 dB RMS with a range 158 to 178 dB RMS for two piles where vibratory levels were measured. Caltrans summarized the project's RMS level as 170 dB RMS (Table I.2-3 in Caltrans 2012), although most levels observed were nominally 160 dB. A fourth project at NBK, Bangor drove 16-inch hollow steel piles, and measured levels similar to those for the 24-inch piles; therefore these data were included in the 24-inch analyses. Although the data set is limited to these four projects, close agreement of the levels (average project values from 159 to 162 dB at 10 meters) indicate similar vibratory conditions at NBK, Bangor. The highest project average of 162 dB was selected as the most reasonable proxy for 24-inch steel pipe piles. This number is higher than the data from the Bangor Test Pile Program and is therefore conservative.

2.1.4.3 30-INCH AND 36-INCH DIAMETER STEEL PIPE PILE VIBRATORY DRIVING SOURCE VALUES

Five projects were reviewed for 30-inch diameter piles and four projects were reviewed for 36-inch diameter piles, with a total sample set of seven projects since some projects used both 30-inch and 36-inch piles. All projects were located in Puget Sound. Because the 30-inch diameter pile average RMS measurements overlap (164 dB, 168 dB, 170 dB, and 171 dB) the measurements reported for 36-inch diameter piles at the Bangor waterfront, the Edmonds and Anacortes ferry terminals range (159 dB, 162.5 dB, 169 dB, respectively), the 30-inch and 36-inch pile data were combined for the review.

We reviewed data from Bangor waterfront projects for 30 and 36-inch piles, which were based on a large sample size relative to other projects (n~68 piles, Attachment 3). RMS vibratory average levels were consistently lower at Bangor than other Puget Sound locations. We recommend using the site-specific data average RMS level for modeling vibratory pile driving at NBK, Bangor, that is, the recommended RMS vibratory installation proxy source value 30-inch to 36-inch diameter piles is 166 dB. Because site specific data is unavailable for all other Navy installations in Puget Sound, we recommend the more conservative proxy value of 167 dB for other Puget Sound Navy sites, which represents the average level for all Puget Sound locations excluding NBK, Bangor for both 30-inch and 36-inch piles.

Table 2-2 summarizes the ranges for the combined size category. Table 2-2 presents reasonable proxy values expected from reviewing values taken from the highest average project SPL for all projects reviewed.

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2.1.4.4 24-INCH STEEL SHEET PILE VIBRATORY DRIVING SOURCE VALUES

Sound levels for vibratory sheet pile driving were reported for three Caltrans projects at the Port of Oakland in San Francisco Bay (see Attachment 3in Appendix A). No data were found for sheet pile driving in Puget Sound. RMS values were only available for one pile at one project and this had an average RMS value of 163 dB. The second project reported 1 sec SEL levels at 10 m for 5 vibratory driven sheet piles. The average per pile SEL ranged from 157 to 160 dB based on the average top and bottom depth measurements. Caltrans also reported 162 dB RMS as the highest average for a single depth for the same project. The third project reported 163 dB RMS (Table I.2-3 in Caltrans 2012). Caltrans reported 160 dB RMS as the typical sheet pile value for all three projects (Table I.2-2 in Caltrans 2012). Based on the levels from the three projects, 163 dB RMS value was used as a conservative proxy value.

2.2 AIRBORNE PILE DRIVING SOURCE VALUES

NMFS has established an in-air noise disturbance threshold of 90 dB RMS re 20µPa (unweighted) for harbor seals, and 100 dB RMS re 20µPa (unweighted) for all other pinnipeds. Attachment 4 and Attachment 5 in Appendix A list the impact and vibratory pile driving projects, respectively, that were reviewed. Most projects report A-weighted levels. For this review, however, only unweighted data were considered. Two airborne noise values are presented for most projects: L_{max} and L_{eq}, The L_{max} is the instantaneous highest sound level measured during a specified period, or maximum noise level. It typically represents a short duration average, usually 35 milliseconds. Because impact pile driving is an impulsive sound with short durations, the signal is most appropriately characterized by the L_{max} value. Proxy values for impact driving are found in Attachment 4.

The L_{eq} is the equivalent steady-state noise level in a stated period of time. It contains the same acoustic energy as the time-varying noise level during the same period. L_{eq} is primarily used for a steadier, non-impulsive noise. The L_{eq}, which averages the source over a period of time, is a better descriptor for non-impulsive sound like vibratory pile driving. These values are listed in Attachment 5 for vibratory pile driving and Table 2-3 summarizes L_{max} and L_{eq} data.

Review of the available literature provided two unweighted L_{max} levels, both from the NBK Bangor Test Pile Program. A maximum level of 112 dB re 20 µPa was measured for 36-inch piles (n=9 piles), at the de facto measurement distance of 50 feet, and was therefore chosen as a conservative proxy value for piles 30 and 36-inches. A maximum level of 110 dB was measured for a single 24-inch pile, and was selected as the most representative value for modeling analysis.

Unweighted RMS L_{eq} values of 88 dB were obtained from vibratory pile driving 18-inch steel pipe piles. A single 30-second measurement was made for 24-inch piles during the Test Pile Program at NBK, Bangor. These data fit the overall trend of smaller and larger pile sizes. The limited data set for 24-inch steel pipe, supports a reasonable representative proxy value of 92 dB.

Limited data were available for 30 and 36-inch piles. One 30-inch pile measured at the Keystone ferry terminal fell within the range of 36-inch piles measured at Bangor., although the

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average value for this was 2 dB above the average value measured at Bangor. Levels measured at Vashon Island ferry terminal were made using A-weighted filters, and adjusted for range and filter type. Even after corrections were made observed levels were significantly lower than other sites, thus these data were not considered for further analysis. We therefore selected 95 dB (unweighted) as the representative L_{eq} average proxy value for 30-inch and 36-inch piles. Based on the limited data available, the RMS L_{eq} value for 18-inch steel pipe piles was chosen as the proxy source value for vibratory installation or removal of piles less than 24-inch regardless of pile type. The RMS L_{eq} value for 24-inch steel pipe piles was chosen as the best estimate for 24-inch sheet piles.

Table 2-3. Summary of Airborne Source Levels. Recommended Proxy Source Values Bolded.[1]

Pile Type	Size (diameter in inches)	Installation Method	
		Impact RMS L_{max} (Unweighted) Impact	Vibratory RMS L_{eq} (Unweighted) Vibratory
Timber	12-inch	---	---
Steel Pipe	18-inch	---	**88**
	24-inch	**110**[2]	**92**[2]
	30-inch	---	**95**
	36-inch	**112**	**95**
Steel Sheet	24-inch	---	---

Notes: All values relative to 20µPa and at 15 m (50 ft) from pile.
[1]See Attachments 4 and 5 in Appendix A for projects reviewed.
[2] Limited data set.

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3.0 EVALUATION OF POTENTIAL BUBBLE CURTAIN SOUND ATTENUATION

To reduce noise produced from impact pile driving, bubble curtains are used around the pile as it is driven and can be confined or unconfined. Confined bubble curtains place a fabric shroud or rigid sleeve around the pile to hold air bubbles near the pile, ensuring they are not washed away by currents or tidal action. They are recommended when water velocities are 0.6 meters (1.6 feet per second) or greater (NMFS 2008).

None of the project locations at Naval Base Kitsap, Naval Magazine Indian Island, Naval Station Everett, Naval Air Station Whidbey Island Seaplane Base, Manchester Fuel Depot are in high current areas; therefore, this discussion focuses on unconfined bubble curtains. Unconfined bubble curtains involve use of pressurized air injected from an air compressor on the pile driving barge through small holes in aluminum or PVC pipe around the driven pile. Noise reduction results from unconfined bubble curtains were reported from several projects. There was a wide range of effectiveness from very little measurable attenuation in some cases to high attenuation in others (Illingworth and Rodkin 2001; WSDOT 2013). Caltrans (2009) summarized the application of unconfined bubble curtain systems in various California projects and reported from 1 to 5 dB of attenuation in high current situations and 5 to 15 dB of attenuation in low current situations. Application of a multiple-ring system in a deep water, strong current setting (Benicia-Martinez Bridge) achieved 15 to more than 30 dB attenuation when driving 8-foot diameter piles. Because some sound pressure waves also propagate from the pile through the substrate and reenter the water column, not all sound pressure waves will be attenuated by a bubble curtain (Reinhall and Dahl 2011). Variability in bubble curtain performance when measured at various distances out from the pile is likely explained by the sound propagation properties of various substrates, the localized bathymetry, as well as variances in embedment depths of piles.

3.1 NOISE ATTENUATION ASSUMPTIONS FOR ACOUSTIC MODELING

The Navy conducted a Test Pile Program at Naval Base Kitsap, Bangor where attenuation of an unconfined bubble curtain was measured when driving 24-inch, 36-inch, and 48-inch steel pipe piles.[5] It should be noted that attenuation measurements were not conducted at EHW-2, and are therefore excluded from calculations herein.[6] Calculations for attenuation were made by calculating the amplitude ratio reduction of the pressure metric with the bubble curtain on compared to the bubble curtain off measurements, and then converting the ratio into a decibel value. Weighted values are computed for each metric based on the number of strikes measured. All measurements were taken from the nominal 10 meter de facto distance from the pile.

[5] Illingworth and Rodkin, 2012
[6] Attenuated measurements from pile installation at EHW-2 in 2012 were similar to nonattenuated measurements from test piles installed in 2011 at the project site, indicating a nonfunctional bubble curtain. Most commonly observed problems reported for non-functional bubble curtains reflect inadequate air-flow or poor seating of the bottom of the curtain at the water-sediment boundary resulting in a non-attenuated sound path.

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The sole 24-inch pile in this project was struck a total of 3 times with the bubble curtain turned on. Therefore, the results are unlikely to be indicative of values that would be obtained on this site with more extensive measurements and are not considered further in this review. Piles for which fewer than 10 strikes were measured were also excluded. It is recommended to acquire a larger 24-inch data set to obtain a better synopsis for these results.

For 36-inch piles the weighted average peak, RMS, and SEL reduction with use of the bubble curtain was 10 dB, where the averages of all bubble-on and bubble-off data were compared (see Table 3-1 below). This data set represents 2 piles, for a total of 165 strikes. For 48-inch piles, the weighted average pressure reduction for RMS, peak, and SEL with use of a bubble curtain was 8 dB, representing 138 strikes. Across all piles (36" and 48") and all metrics (RMS, peak, SEL), the weighted average attenuation was 9 dB.

Table 3-1. Reduction (dB) in Weighted Average Noise Values for Impact Pile Driving of Steel Piles with a Bubble Curtain. Measured at 10 Meters Averaging Mid-Depth and Deep-Depth Data. Measurements Obtained during Bangor Naval Base Test Pile Program.

Pile Size	Attenuation Level (RMS)		Attenuation Level (Peak)		Attenuation Level (SEL)		Weighted Average (all metrics)
	Weighted	Unweighted	Weighted	Unweighted	Weighted	Unweighted	
36-inch	9	9	11	11	10	10	10
48-inch	7	7	9	9	7	7	8
Overall weighted average							9
Source: Illingworth & Rodkin 2012							

We also reviewed unconfined bubble curtain attenuation rates from available reports from projects in Washington, California, and Oregon that impact drove steel pipe piles up to 48-inches in diameter. Table 3-2 contains a summary of the attenuation levels reported. Several studies were reviewed, but not included in the summary because they were not considered representative. Excluded studies were:

- Willamette River Bridge Project (Caltrans 2012). Bubble curtain was poorly designed and deployed in a river with a high current. No RMS SPLs reported.
- South Umpqua River (Caltrans 2012). Current conditions resulted in little coverage of piles by bubble curtain. No RMS SPLs reported.
- Ten Mile River Bridge Project (Caltrans 2012). 30-inch piles driven with bubble curtain, but inside of cofferdam.

Of the remaining studies reviewed, significant variability in attenuation occurred; however, an average of at least 8 dB of peak SPL attenuation was achieved on ten of the twelve projects (Table 3-2). Some of the lower attenuation levels reported were attributed to the bottom ring not seated on the substrate, poor airflow, or currents that resulted in an uneven distribution of bubbles (WSDOT 2005a, WSDOT 2005b, Caltrans 2012).

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Table 3-2. Summary of Attenuation Levels Reported with Unconfined Bubble Curtains During Impact Driving of Steel Pipe Piles up to 40-inches Diameter.

Project/Location	Steel Pipe Pile Diameter	Range (dB)	Mean Peak dB re 1μPa @ 10 m	Standard Deviation (dB)
Friday Harbor Ferry Terminal Restoration/ San Juan Island marine waters, WA[1]	24-inch 30-inch	0-5	2	2.2
Bainbridge Island Ferry Terminal Preservation/ Puget Sound marine waters, WA[1]	24-inch	3-14	7	4.7
Cape Disappointment Boat Launch Facility, Wave Barrier Project/ Columbia River, Illwaco, WA[1]	12-inch (n=5*)	6-17	11	4.9
Mukilteo Ferry Terminal Test Pile/Puget Sound marine waters, WA[1]	36-inch (n=2)	7-22	15	10.6
Anacortes Ferry Terminal Dolphin Replacement/Puget Sound marine waters, WA[1]	36-inch (n=7)	3-11	8	3.1
SR 520 Test Pile Project/Lake Washington/Portage Bay (freshwater), WA[1, 2]	24-inch (n=4) 30-inch (n=2)	3-32	20	11.1
Columbia River Crossing Test Pile Program/Columbia River, WA/OR[3]	24-inch (n=1)	---	10	---
Tesoro's Amorco Wharf/San Francisco Bay, Martinez, CA[2]	24-inch (n=8 battered and n=18 vertical)	---	~10 dB (not well seated, stated capable of up to 15 dB and strong currents present at times and poor positioning on some piles)*	---
Deep Water-tongue Point Facility Pier Repairs/Columbia River, Astoria, OR[2]	24-inch (n=10)	5-22	14	---
Portland-Milwaukie Light Rail Project/Willamette River, Portland, OR[2]	24-inch (n=5)	8-27	---	---
Bay Ship and Yacht Dock/San Francisco Bay, Almeda, CA[2]	40-inch (n=2)	---	~10-15 (Not installed at the substrate at start of drive. Performance from part of drive when bubble curtain properly situated).*	---
Richmond-San Rafael Bridge Project/San Francisco Bay, CA[2]	30-inch (n=2)	---	9	---

Sources: [1]WSDOT 2013, Also, see individual report references for WSDOT; [2]Caltrans 2012; [3]CRC 2011.
*As reported by Illingworth and Rodkin in Caltrans 2012.

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In summary, bubble curtain performance is highly variable. Effectiveness depends on the system design and on-site conditions such as water depth, water current velocity, substrate and underlying geology. Installation and how well the curtain is seated on the substrate at the bottom are also important factors. To avoid loss of attenuation from design and implementation errors, our project has specific bubble curtain design specifications, including testing requirements for air pressure and flow prior to initial impact hammer use, and a requirement for placement on the substrate.

While bubble curtain performance is variable, we believe that, based on information from the Bangor Naval Base Test Pile Program, an average peak SPL[7] reduction of 8 dB to 10 dB at 10 meters would be an achievable level of attenuation for steel pipe piles of 36- and 48-inches in diameter. However, to be more conservative for 48 inch piles, use of 7 dB for both RMS and SEL metrics is justified.

[7] For most of the studies reviewed, Peak SPLs were the only metric reported.

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4.0 REFERENCES

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2) Caltrans. 2012. Compendium of Pile Driving Sound Data. Sacramento, California. Updated October 2012, posted March 20, 2013. Available at http://www.dot.ca.gov/hq/env/bio/fisheries_bioacoustics.htm.

3) CRC (Columbia River Crossing). 2011. Columbia River Crossing test pile project hydroacoustic monitoring final report. Technical report prepared by David Evans and Associates, Inc. July 2011. Available at http://www.columbiarivercrossing.org/filelibrary/technicalreports/CRC_Pile_R.

4) Illingworth and Rodkin, Inc. 2001. Noise and vibration measurements associated with the pile installation demonstration project for the San Francisco-Oakland Bay Bridge East Span, Final Data Report, Task Order 2, Contract No. 43A0063.

5) Longmuir, C. and T. Lively. 2001. Bubble curtain systems for use during marine pile driving. Produced by Fraser River Pile & Dredge, Ltd.

6) MacGillivray, Al, Ziegler, E. and J. Laughlin. 2007. Underwater acoustic measurements from Washington State Ferries 2006 Mukilteo ferry terminal test pile project. Technical report prepared by JASCO Research, Ltd for Washington State Ferries and Washington State Department of Transportation, 27 pp. Available at http://www.wsdot.wa.gov/environment/air/piledrivigreports.htm.

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8) Navy (Department of the Navy). 2013. Naval Base Kitsap, Bangor Explosives Handling Wharf-2 acoustic monitoring report. Prepared by Illingworth and Rodkin, Inc. for the U.S. Navy.

9) Reinhall, P.G. and P.H. Dahl. 2011. Underwater Mach wave radiation from impact pile driving; theory and observation. Journal of the Acoustical Society of America 130:120-1216.

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10) NMFS (National Marine Fisheries Service). 2008. Programmatic Biological Opinion and Magnuson-Stevens Fishery Conservation and Management Act Essential Fish Habitat Consultation for Revisions to Standard Local Operating Procedures for Endangered Species to Administer Maintenance or Improvement of Road, Culvert, Bridge and Utility Line Actions Authorized or Carried Out by the U.S. Army Corps of Engineers in Oregon (SLOPES IV Roads, Culverts, Bridges and Utility Lines). National Marine Fisheries Service, Northwest Region, August 13, 2008.

11) WSDOT (Washington Department of Transportation). 2005a. Underwater sound levels associated with restoration of the Friday Harbor Ferry Terminal. May 2005. Available at http://www.wsdot.wa.gov/environment/air/piledrivingreaports.htm.

12) WSDOT. 2005b. Underwater sound levels associated with pile driving at the Bainbridge Island ferry terminal preservation project. November 2005. Available at http://www.wsdot.wa.gov/environment/air/piledrivingreports.htm.

13) WSDOT. 2006. Underwater sound levels associated with pile driving at the Cape Disappointment boat launch facility, wave barrier project. March 2006. Available at http://www.wsdot.wa.gov/environment/air/piledrivingreports.htm.

14) WSDOT. 2007. Underwater sound levels associated with pile driving during the Anacortes ferry terminal dolphin replacement project. April 2007. Available at http://www.wsdot.wa.gov/environment/air/piledrivingreports.htm.

15) WSDOT. 2010. Underwater sound levels associated with driving steel piles for the State Route 520 bridge replacement and HOV project pile installation test program. Prepared by Illingworth and Rodkin, Inc. Available at http://www.wsdot.wa.gov/environment/air/piledrivingreports.htm.

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APPENDIX A

STUDIES REVIEWED FOR EVALUATION OF UNDERWATER PILE DRIVING SOUND

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Appendix A: Studies Reviewed for Evaluation of Underwater Pile Driving Sound

Attachment 1. Impact Pile Driving SPLs from Studies Utilizing Steel Pipe/CISS Piles. Bolded values were considered for proxy source levels.

Project	Location	Number of Piles Measured	Hammer Type	Water Depth (m)	Distance (m)	RMS (dB re 1 µPa)	Peak (dB re 1 µPa)	SEL (dB re 1 µPa^{2}s)
24-inch Steel Pipe								
Bainbridge Island Ferry Terminal[1]	**Bainbridge Island, WA**	**n=5**	**Diesel**	**2.1-3.4**	**10**	**Weighted Ave 195 Ave range 193-198**	**Weighted Ave 206 Ave range 202-209**	**Weighted Ave 181 Ave range 177-184**
Friday Harbor Ferry Terminal[2]	**Friday Harbor, WA**	**n=5**	**Diesel, pneumatic, hydraulic**	**10-14.3*, ****	**10**	**Weighted Ave 189 Ave range 181-193**	**Weighted Ave 207 Ave range 196-213**	**Weighted Ave 181 Ave range 176-185**
Bangor Test Pile Program[3]	Bangor Naval Base, WA	† n=1	Impact	4.6	10	Max 180	Max 193	Ave 167
Conoco/Phillips Dock [4]	Rodeo, San Francisco Bay, CA	n=2	Diesel	>5	10	Range 188-189	203 (unclear if this is average or ave max)	Typical 177 Range 177-178
Tesoro's Amorco Wharf- all values were attenuated- values reported are mostly unattenuated – strong currents present[4]	San Francisco Bay; Martinez, CA	(1st pile with poor attenuation)	Diesel	10-15	10	189	Max 209	174
Deep Water-Tongue Point Facility Pier Repairs[4]	Mouth of Columbia River; Astoria, OR	n=10	Diesel	unknown	10	Ave 182 Ave range 178-189	Ave max 198 Range 193-206 Max 207	Ave 168 Ave range 160-175
30-inch Steel Pipe								
Richmond-San Rafael Bridge, CALTRANS[4]	San Rafael, CA	n=4	Diesel	4-5	10	Typical 190 (max=192)	210 max (typical 205)	---
Eagle Harbor Maintenance Facility[5]	**Bainbridge Island, WA**	**n=3**	**Diesel**	**10**	**10 (n=2) 16 (n=1)**	**Weighted Ave 192 Ave range 192-193**	**Weighted Ave 204 Ave range 203-204**	**---*****
Friday Harbor Ferry Terminal #8[2]	**Friday Harbor, WA**	**n=1**	**Diesel**	**10.4***	**10**	**196**	**211**	**187**
Vashon Ferry Terminal[6,#]	**Vashon Island, WA**	**n=3**	**Diesel**	**11-12**	**10**	**Weighted Ave 195 Ave range 192-196**	**Weighted Ave 215 Ave range 212-217**	**Weighted Ave 186 Ave range 182-187**

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Attachment 1. Impact Pile Driving SPLs from Studies Utilizing Steel Pipe/CISS Piles (continued). Bolded values were considered for proxy source levels.

Project	Location	Number of Piles Measured	Hammer Type	Water Depth (m)	Distance (m)	RMS (dB re 1 μPa)	Peak (dB re 1 μPa)	SEL (dB re 1 μPa²s)
36-inch Steel Pipe****								
Humboldt Bay Bridge[4]	Humboldt Bay – Eureka, CA	CISS n=1, restrikes	Diesel	10	10-	193 (max)	210 (max)	183 (max)
Mukilteo Test Piles[7]	**Mukilteo, WA**	**n=2**	**Diesel**	**7.3**	**10**	**Weighted Ave 190 Ave range 187-191**	**Weighted Ave 205 Ave range 202-207**	**Weighted Ave 183 Ave range 180-184**
Anacortes Ferry[8]	**Anacortes, WA**	**n=7**	**Impact**	**12.8**	**10**	**Weighted Ave 192 Ave range 189-193**	**Weighted Ave 209 Ave range 205-211**	**Weighted Ave 185 Ave range 183-186**
Bangor Test Pile Program[3,#]	**Bangor Naval Base, WA**	**n=4**	**Diesel**	**13.7-26.8**	**10**	**Weighted Ave 194 Ave range 185-196**	**---^**	**Weighted Ave 181 Ave range 173-183**

Notes: Ave = Average.
* Substrate was sandy silt/clay.
** Substrate was sandy silt/rock.
*** Single strike SEL not reported.
****EHW-2 project at Bangor waterfront measured 24- and 36-inch piles; however, all piles were attenuated so they are not included in the table. 24-inch (n = 41) averages were: average peak = 199 (s.d. 9.58), average RMS = 179 (s.d. = 24.10), SEL = 170 dB (s.d. = 7.48). 36-inch pile (n = 26): average peak = 205 (s.d. = 4.33), average RMS = 188 (s.d. = 5.01), average SEL = 175 (s.d. = 5.11) (Navy 2013).
† 24-inch piles were not hit very hard, so these are not representative of the levels that may occur in the future or elsewhere.
\# distance to pile ranged above and below 10m. Data normalized to 10m using $15\log_{10}$ (range/10m) relationship.
^ Average peak values not reported.

Sources:
[1] WSDOT 2005a
[2] WSDOT 2005b
[3] Navy 2012
[4] Caltrans 2012
[5] JASCO Research. 2005, WSDOT 2008
[6] WSDOT 2010b
[7] WSDOT 2007a
[8] WSDOT 2007b

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Attachment 2. Impact Pile Driving SPLs from Studies Utilizing Concrete Piles.
Bolded values were considered for proxy source levels.

Project	Location	Number of Piles Measured	Hammer Type	Water Depth (m)	Distance (m)	RMS (dB re 1 µPa)	Peak (dB re 1 µPa)	SEL (dB re 1 µPa^{2}s)
16-inch and 18-inch Piles								
Pier 2 Concord NWS[1] (16-inch square)	**Concord, CA**	**n=5**	**Drop Steam Powered**	**7**	**10**	**Ave 171 Ave range 167-173**	**Ave max 183 Ave max range 182-184 Max 184**	**N/A**
Berkeley Marina (2007) [1] (18-inch octagonal)	**Berkeley, CA**	**n=1**	**Diesel**	**2-3**	**10**	**Ave 159 Ave range 155-167**	**Ave max 172 Ave range 172-181 Max 181**	**Ave 155**
Berkeley Marina (2009) [1] (18-inch octagonal)	**Berkeley, CA**	**n=3**	**Diesel**	**2-3**	**10**	**Ave 169 Ave range 165-178**	**Ave max 189 Ave max range 184-192 Max 192**	**Ave 159**
24-inch Piles								
Mukilteo Ferry Terminal[2] (octagonal)	**Mukilteo, WA**	**n=1**	**Diesel**	**7-8**	**10**	**Ave 170 (single pile)**	**Ave max 184 Single pile**	**Ave 159 dB Range 159-170**
Amports Pier 95[1] (octagonal)	**Benicia, CA**	**Not provided**	**Diesel**	**3-7**	**10**	**Ave 170 Range 168-172**	**Ave max 184 Range 180-192 Max 192**	**N/A**
Pier 40 Marina[1] (square)	**San Francisco, CA**	**n=7**	**Diesel**	**3-4**	**10**	**Ave 171 Ave range 167-174**	**Ave max 184 Ave range 180-186 Max 186**	**N/A**
Berth 22 Port of Oakland (December 2004)[1] (octagonal)	**Oakland, CA**	**Several**	**Diesel**	**0-15 (dependent on row)**	**10 (mostly)**	**Ave 176*** Ave range*** 171-179 Max 181**	**Ave max 188*** Ave max range*** 183-191 Max 193**	**Ave 165*** Ave range** 162-167**
Berth 22 Port of Oakland (August 2004)[1] (octagonal)	**Oakland, CA**	**n=4**	**Diesel**	**10-13**	**10**	**Ave 175 Ave range during loudest part of drive 174-176 Max 178**	**Ave max 187 Ave max range during loudest part of drive 186-188 Max 190**	**Ave 165 Ave range during loudest part of drive 164-166 Max 168**

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Attachment 2. Impact Pile Driving SPLs from Studies Utilizing Concrete Piles (continued). Bolded values were considered for proxy source levels.

Project	Location	Number of Piles Measured	Hammer Type	Water Depth (m)	Distance (m)	RMS (dB re 1 µPa)	Peak (dB re 1 µPa)	SEL (dB re 1 µPa^{2}s)
Berth 32 Port of Oakland (2005)[1] (octagonal)	**Oakland, CA**	**n=2**	**Diesel**	**3-7**	**10**	**Ave 174 Ave range 172-176**	**Ave max 186 Ave max range 185-187 Max 187**	**Ave 163 Ave range 158-165**
Berth 32 Port of Oakland (2004)[1] (octagonal)	**Oakland, CA**	**n=5**	**Diesel**	**>10**	**10**	**Ave 173 Ave range 173-174**	**Ave max 185 Ave max range 184-185 Max 185**	**Ave 162 Ave range 161-163**
Humboldt State University Floating Dock****[1] **(octagonal)**	Humboldt Bay, Eureka, CA	n=3	Diesel	3-4	10	Ave 157 Ave range 156-158	Ave max 179 Ave max range 176-179 Max 179	Ave 148 Ave range 142-151

Notes: Ave = Average.
* For piles with fuel setting on high, no jetting.
**Pile with fuel setting on low, no jetting.
*** Average for row, not pile. Sound levels varied by depth. Only in-water sound levels reported in table (unattenuated values from Row A-D in Table 1.5-4 in Caltrans 2013).
****Piles jetted, so project data is not included in analysis.

Sources:
[1] Caltrans 2012
[2] WSDOT 2007a

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Attachment 3. Vibratory Pile Driving SPLs from Marine Projects. Bolded values were considered for proxy source levels.

Project	Location	Number of Piles Measured	Water Depth (meters)	Distance (meters)	Mean RMS* dB re 1 µPa
12-inch Timber					
Port Townsend Dolphin Timber Pile Removal[1]	**Port Townsend, WA**	**n=1**	**---**	**16**	**Average 150 Range 149-152**
13-inch Steel Pipe					
Mad River Slough Pipeline Construction[2]	Mad River Slough, Arcata, CA	n=3	4.5-5.5	10	155
16-inch Steel Pipe					
EHW-1[3]	**Bangor, WA**	**n=8**	**9-12**	**10**	**162 Ave range 153-168**
24-inch Steel Pipe					
Friday Harbor[4]	**Friday Harbor, WA**	**n=1**	**2.6**	**10**	**162**
Trinidad Pier Reconstruction[2]	**Trinidad Bay, Humbolt County, CA**	**n=2**	**15.2**	**10**	**Typical 160 range 158-178**
Bangor Test Pile Program[5]	**Bangor Naval Base, WA**	**n=2 (1 pile vibed in and out)**	**4.6**	**10**	**160 Ave range 157-160****
30-inch Steel Pipe					
Edmonds[6]	**Edmonds, WA**	**n=2**	**6.4**	**10**	**165-166**
Keystone Ferry Terminal[7]	**Coupeville, WA**	**n=4**	**~9.4**	**10 11 6 11**	**Per pile values due to different distances (165 176 176 165) Ave 173 Ave range 165-176**
Vashon Ferry Terminal[8]	**Vashon Island, WA**	**n=4**	**<6**	**11-16**	**167 Ave range 160 - 169**
Port Townsend Test Pile Project[9, 10]	**Port Townsend, WA**	**n=1**	**8.8**	**10**	**170 Ave range 164-174**
EHW-1[3]	**Bangor, WA**	**n=35**	**9-12**	**10**	**168 Ave range 155-174**
36-inch Steel Pipe					
Edmonds Ferry Terminal[6]	**Edmonds, WA**	**n=2**	**5.8**	**11**	**Ave range 162-163**
Anacortes Ferry Terminal[11]	**Anacortes, WA**	**n=2**	**12.7**	**11**	**Ave range 168-170**
Port Townsend Test Pile Project[9, 10]	**Port Townsend, WA**	**n=1**	**9.5**	**10**	**172 159-177**
Bangor Test Pile Program[5]	**Bangor Naval Base, WA**	**n=~33**	**13.7-26.8**	**10**	**164 **** **Ave range 154-169**

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Attachment 3. Vibratory Pile Driving SPLs from Marine Projects (continued). Bolded values were considered for proxy source levels.

Project	Location	Number of Piles Measured	Water Depth (meters)	Distance (meters)	Mean RMS* dB re 1 µPa
24-inch AZ25 Steel Sheet					
Berth 23, Port of Oakland[2]	**Oakland, CA**	**n=1**	**~12-14**	**10**	**163*****
Berth 30, Port of Oakland[2]	**Oakland, CA**	**n=5**	**~12**	**10**	1-sec SEL**** = **159** **Ave range 157-160 (162 highest ave from bottom depth)**
Berth 35/37, Port of Oakland[2]	**Oakland, CA**	**---**	**15**	**10**	**163**

Notes: Ave = Average.
*WSDOT typically reports average of 30-second RMS values calculated over the duration of a drive.
** Average of all pile driving events.
***Involved only stabbing. Average reported by Caltrans Table I-1.2-3.
****RMS SPLs were not reported, but would be similar to SEL for 1 second. Average top and bottom depths.

Sources:
[1] WSDOT 2011a
[2]Caltrans 2012
[3]Miner 2012
[4]WSDOT 2010a
[5] Navy 2012
[6] WSDOT 2011b
[7]WSDOT 2010c
[8]WSDOT 2010d
[9] WSDOT 2010e
[10] Laughlin 2010
[11] WSDOT 2012
* Sound attenuation used water jetting and cushion blocks.
** Water jetting data were excluded from analysis data set.
[1] Caltrans 2012

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Attachment 4. Impact Pile Driving Lmax Airborne SPL Studies.
Bolded projects were considered for proxy source levels.

Project	Location	Number of Piles Measured	Distance (meters/feet)	L_{max} dB re 20 µPa
12-inch Steel Pipe				
Cape Disappointment Boat Launch Facility, Wave Barrier Project[1]	Columbia River, Astoria, OR	1 at 50 m	50 m/164 ft	89 A-weighted
24-inch Steel Pipe				
Bangor Test Pile Program	**Bangor Naval Base, WA**	**1**	**15.2 m/50 ft** **121.9 m/400 ft**	**110 dB (109 dBA)** **95 dB (93 dBA)**
SR 520 Bridge Replacement Test Pile[2]	Portage Bay, Seattle, WA	2	11-15 m/36-49 ft	95-100 dBA
30-inch Steel Pipe				
Friday Harbor Ferry Terminal Restoration[3]	San Juan Island Area, Friday Harbor, WA	1	49 m/160 ft	---
SR 520 Bridge Replacement Test Pile[2]	Union Bay, Lake Washington, Seattle, WA	4	11-15 m/36-49 ft	103-106 dBA
36-inch Steel Pipe				
Bangor Test Pile Program[4]	**Bangor Naval Base, WA**	**---**	**15 m/50 ft**	**109 dB (s.d.=2.58)** **Range 106-112 dB**

Notes: All values unweighted unless indicated. Only unweighted values were considered for proxy values.

Sources:
[1] WSDOT 2006
[2]WSDOT 2010f
[3]WSDOT 2005b
[4] Navy 2012

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Attachment 5. Vibratory Pile Driving L_{eq} Airborne SPL Studies. Bolded projects were considered for proxy source levels.

Project	Location	Number of Piles Measured	Distance (meters/feet)	Average RMS L_{eq} dB re 20 µPa*	Average RMS L_{eq} dBA re 20 µPa*
18-inch Steel Pipe					
Wahkiakum Ferry Terminal [1]	**Columbia River, WA**	**1**	**15.2 m/50 ft***	**87.5**	
24-inch Steel Pipe					
Bangor Test Pile Program	Bangor Naval Base, WA	1	15.2 m/50 ft 121.9 m/400 ft	92 78 dB	85 72
SR 520 Bridge Replacement Test Pile[2]	Portage Bay, Seattle, WA	1	11 m/36 ft	88 dBA	---
30-inch Steel Pipe					
Keystone Ferry Terminal[1]	**Puget Sound, WA**	**1**	**15.2 m/50 ft***	**95 Range 93-96**	
Vashon Ferry Terminal Test Pile Project[1,3]	Puget Sound, Vashon Island, WA	2	15.2 m/50 ft*	~83-85**	~77-80 dBA*
36-inch Steel Pipe					
Bangor Test Pile Program[4]	**Bangor Naval Base, WA**	**---**	**15 m/50 ft**	**93 (s.d.=3.08) Range 89-102**	

Notes: All values unweighted unless indicated.
* Sound pressure levels standardized to 50 ft range. Measurements made at 11 meters
**Converted to C-weighted from A-weighted measurements to approximate unweighted sound level, reported at a distance of 26 to 36 feet.

Sources:
[1] WSDOT 2010g
[2] WSDOT 2010f
[3] WSDOT 2010d
[4] Navy 2012

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APPENDIX B

DATA CHARTS FOR MEASURED DATA AND CUMULATIVE PROBABILITY DISTRIBUTION FUNCTIONS

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Appendix B: Data Charts for Measured Data and Cumulative Probability Distribution Functions

Impact RMS

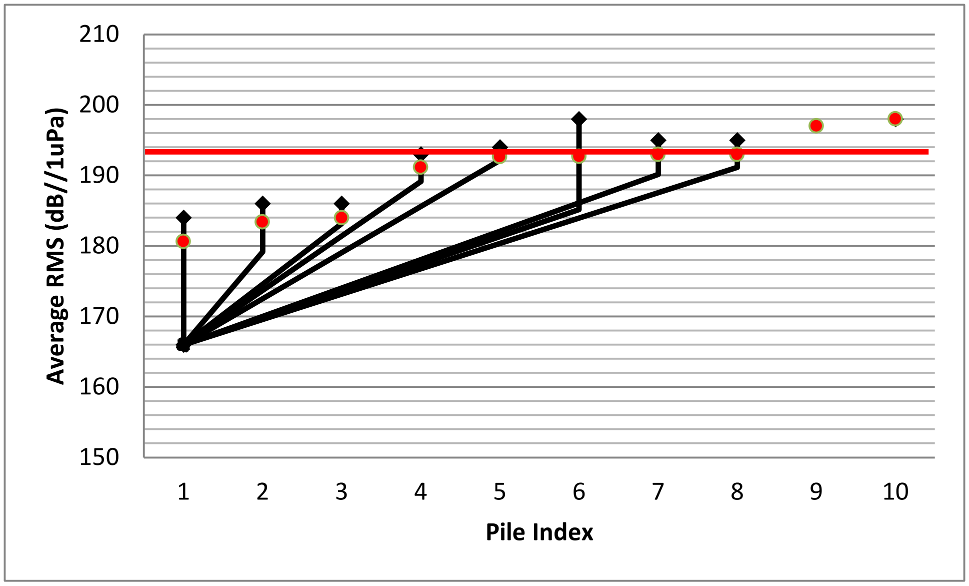

Figure B-1. 24-inch RMS Measurements

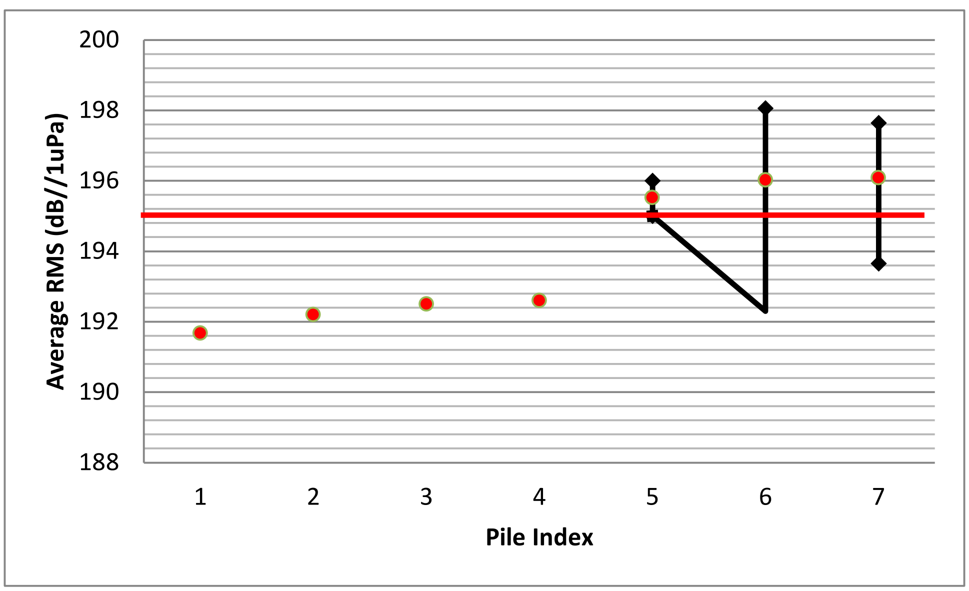

Figure B-2. 30-inch RMS Measurements

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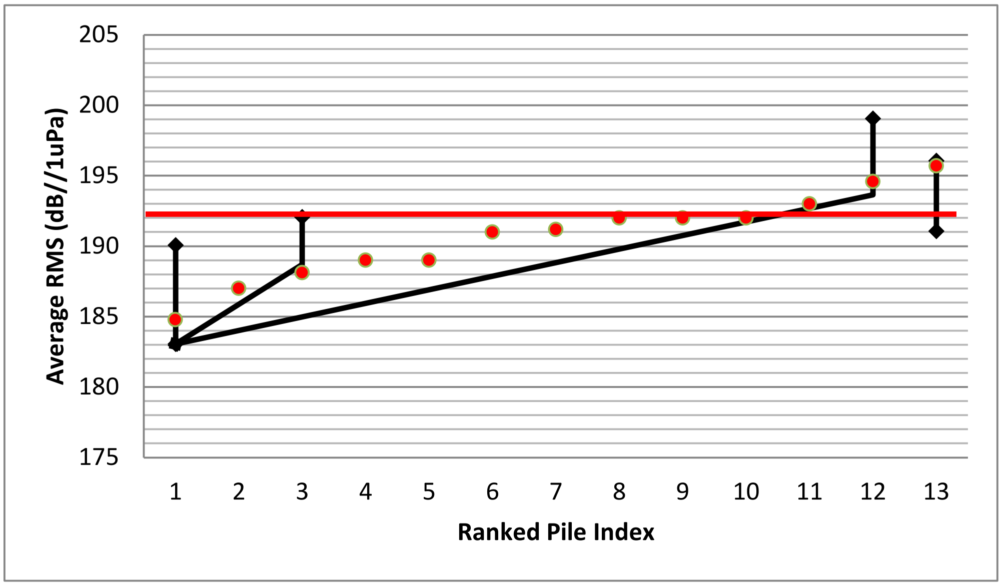

Figure B-3. 36-inch RMS Measurements

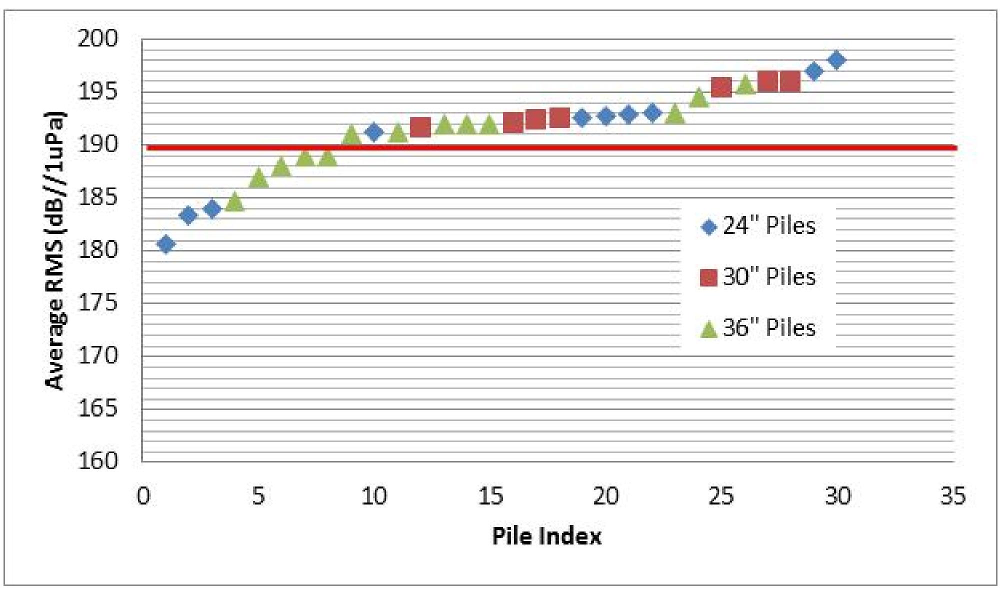

Figure B-4. Combined Analysis: 24, 30, 36-inch RMS Measurements

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Impact Average Peak

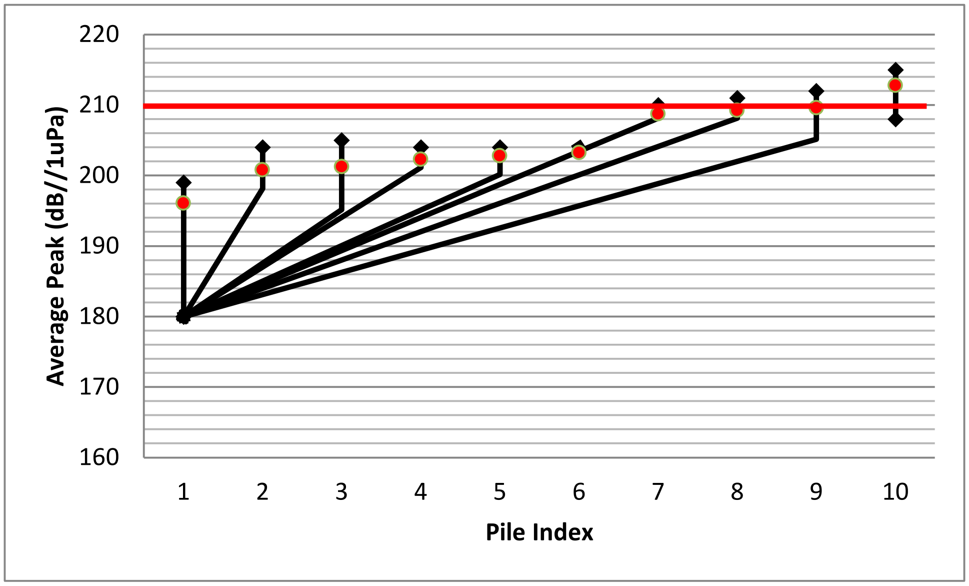

Figure B-5. 24-inch Average Peak Measurements

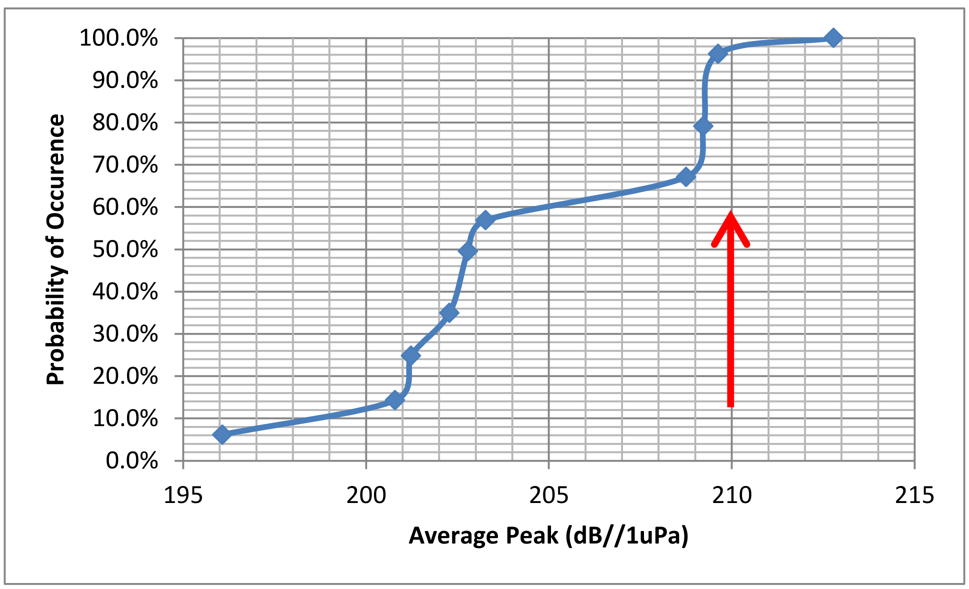

Figure B-6. 24-inch Average Peak Cumulative Distribution Function

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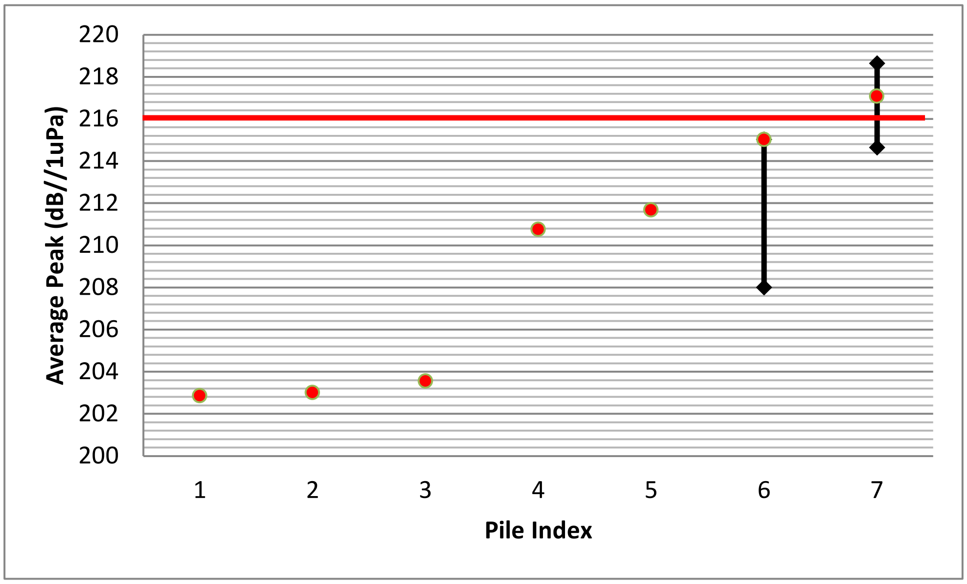

Figure B-7. 30-inch Average Peak Measurements

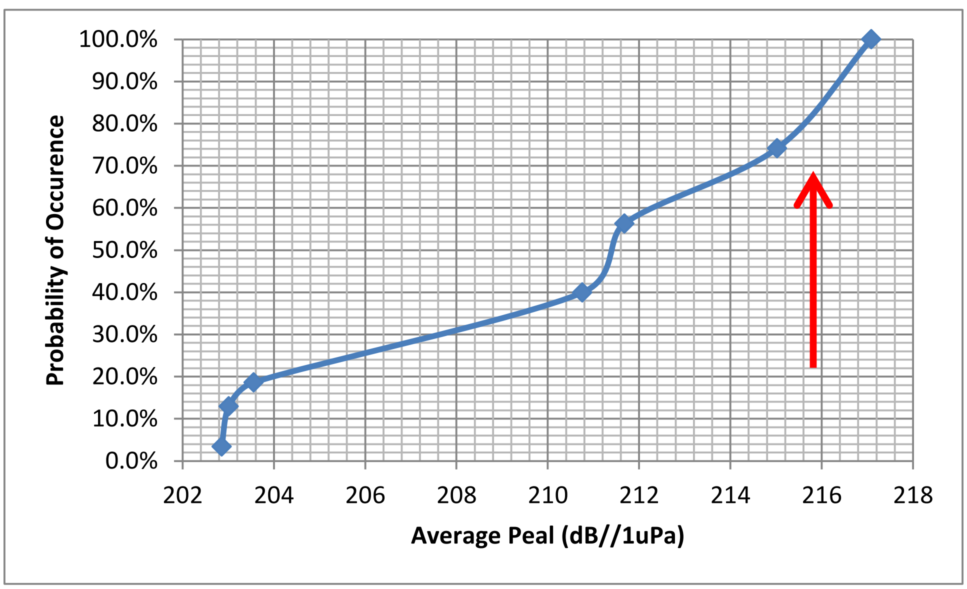

Figure B-8. 30-inch Average Peak Cumulative Distribution Function

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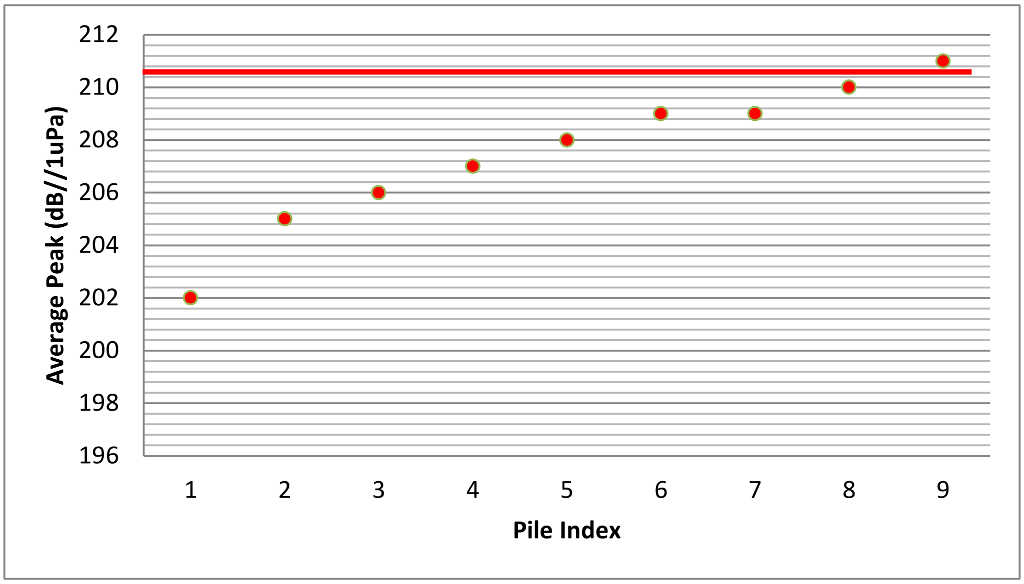

Figure B-9. 36-inch Average Peak Measurements

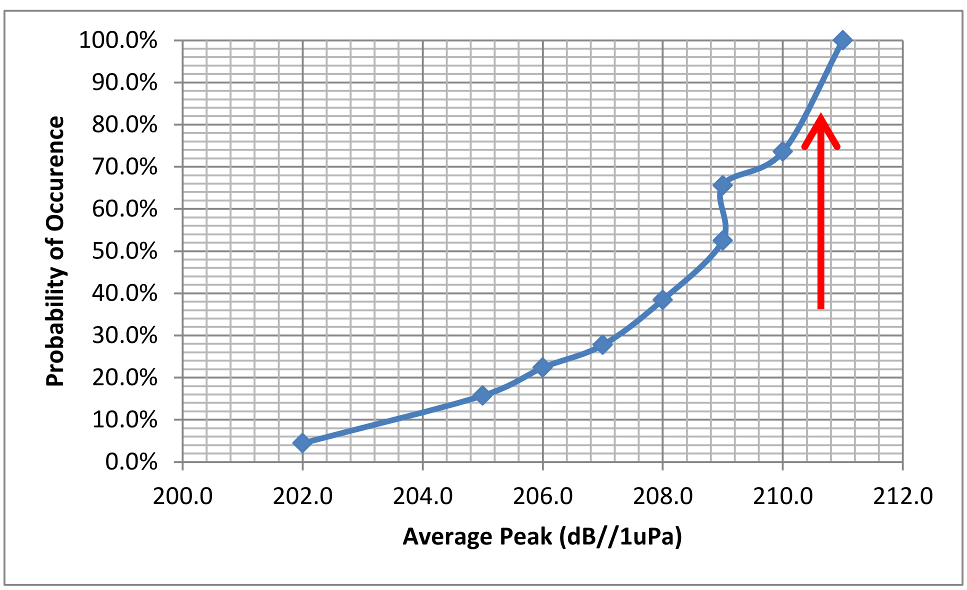

Figure B-10. 36-inch Average Peak Cumulative Distribution Function

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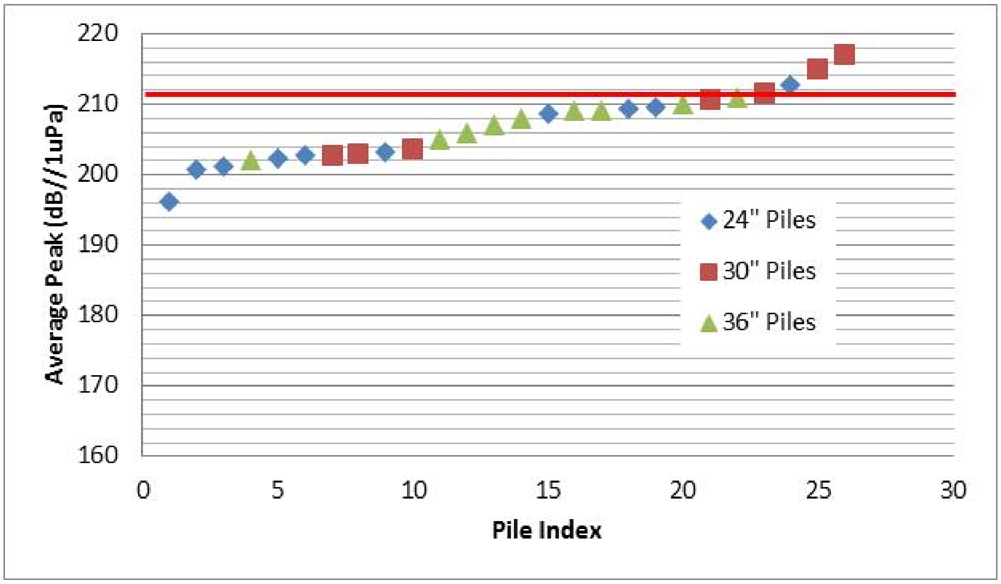

Figure B-11. Combined Analysis: 24, 30, 36-inch Average Peak Measurements

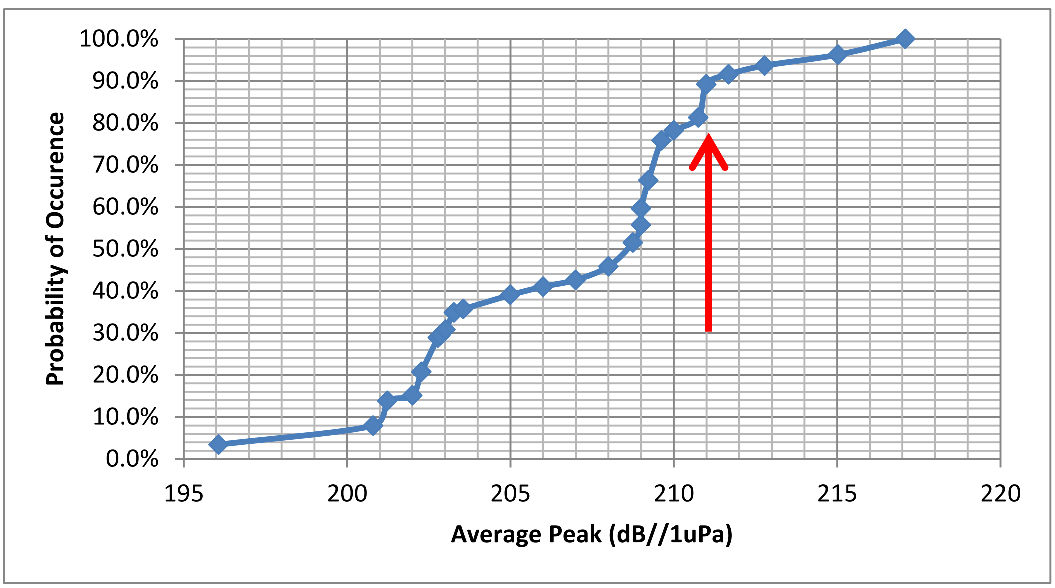

Figure B-12. Combined Analysis: 24, 30, 36-inch Average Peak Cumulative Distribution Function

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Impact SEL

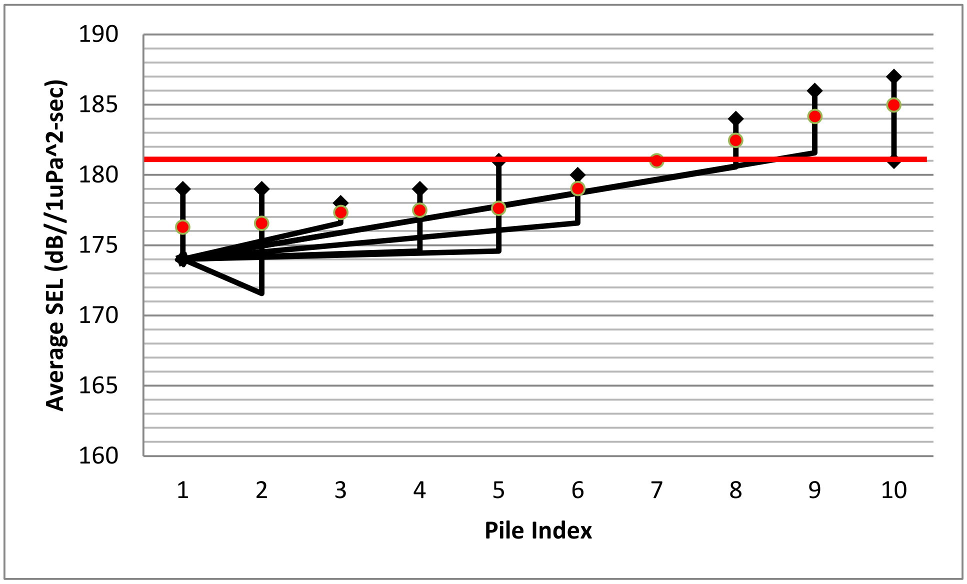

Figure B-13. 24-inch SEL Measurements

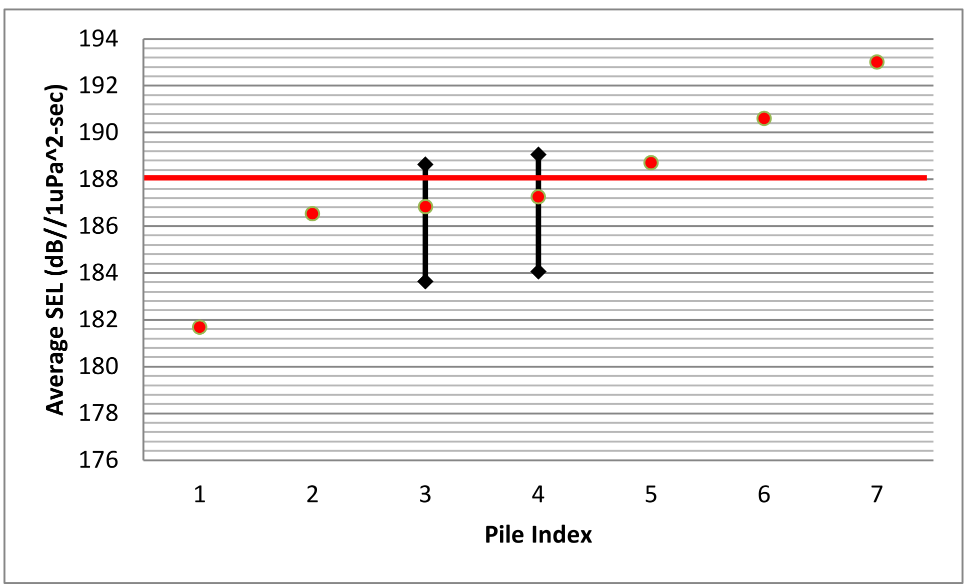

Figure B-14. 30-inch SEL Measurements

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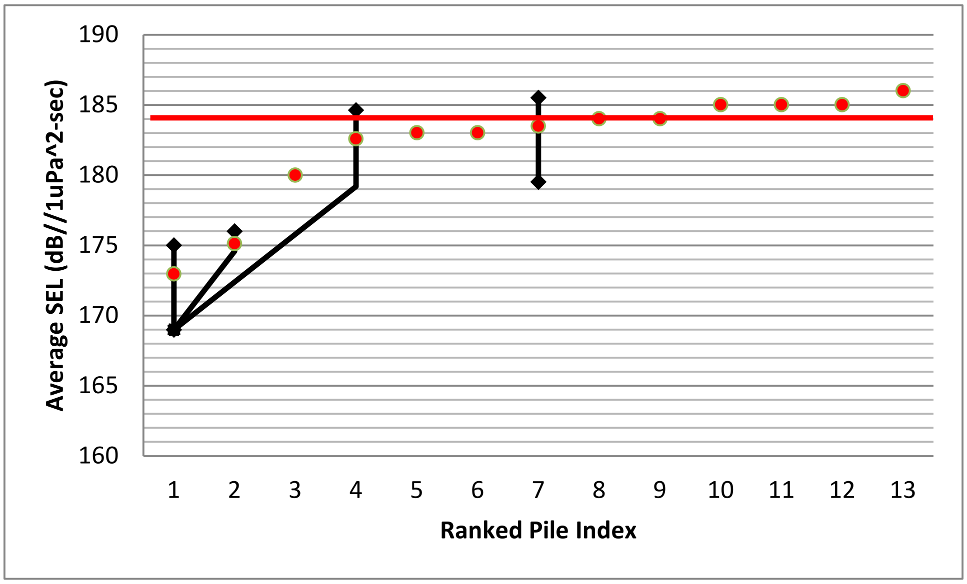

Figure B-15. 36-inch SEL Measurements

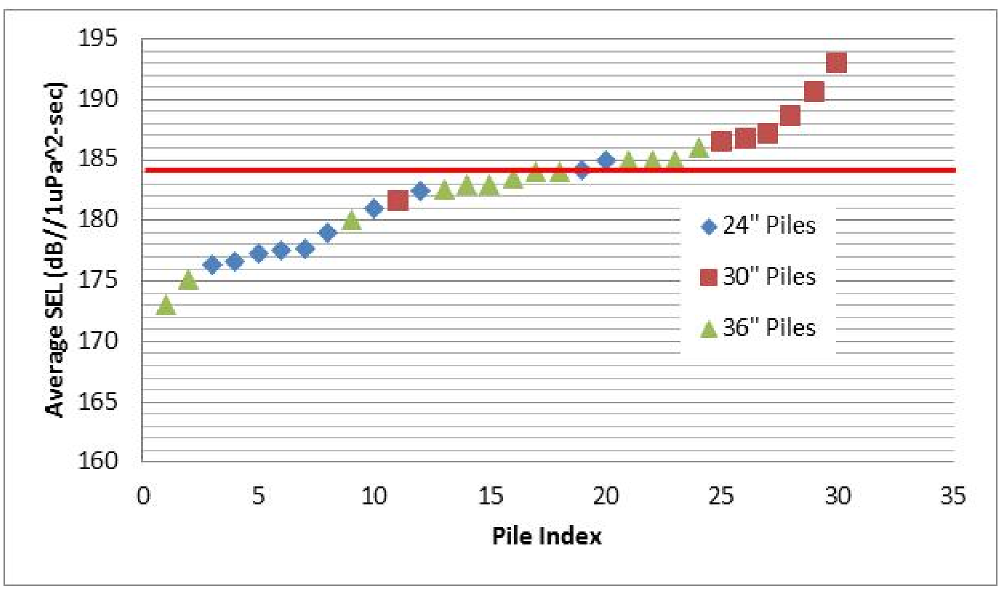

Figure B-16. Combined Analysis: 24, 30, 36-inch SEL Measurements

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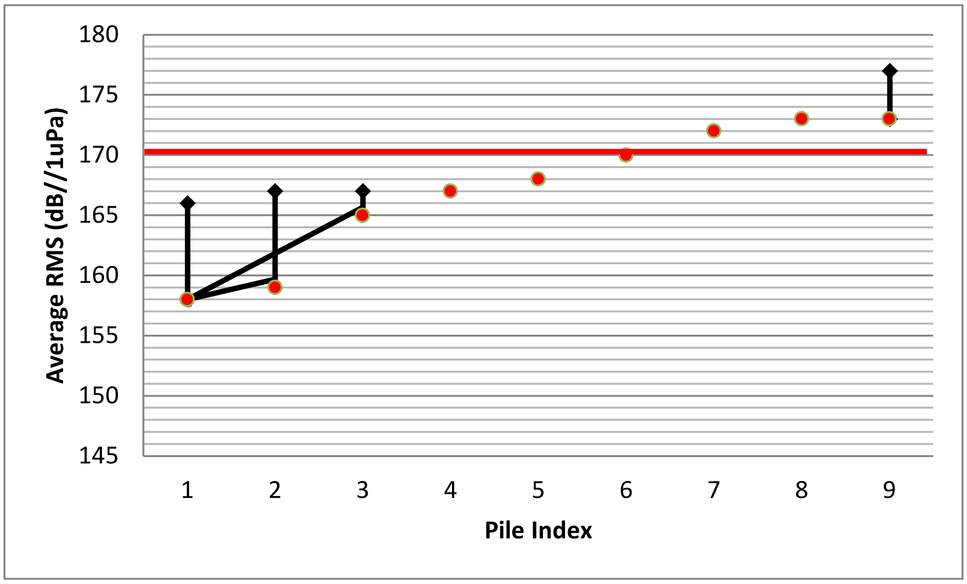

Figure B-17. Concrete 16, 18-inch RMS Measurements

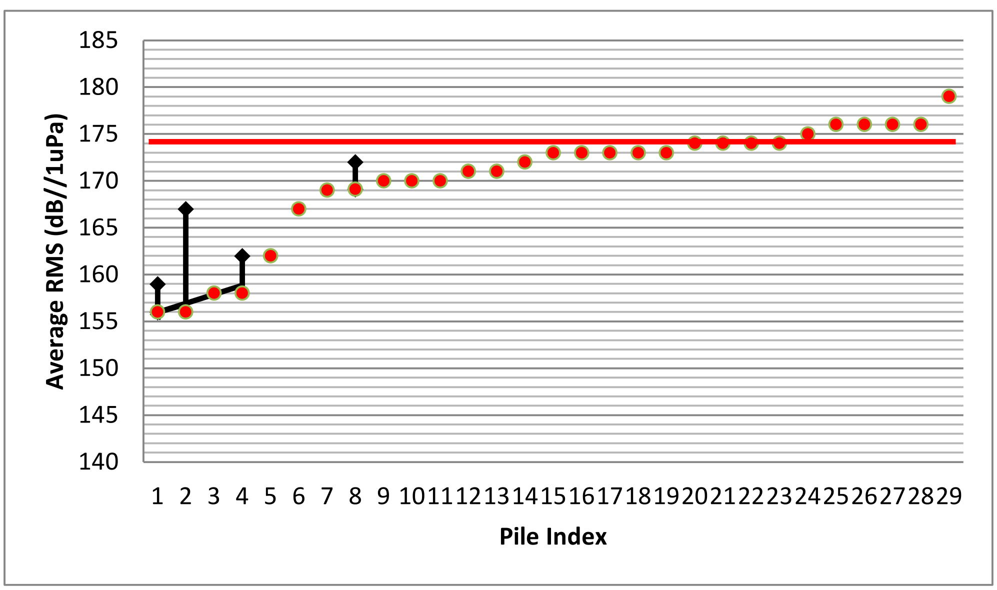

Figure B-18. Concrete 24-inch RMS Measurements

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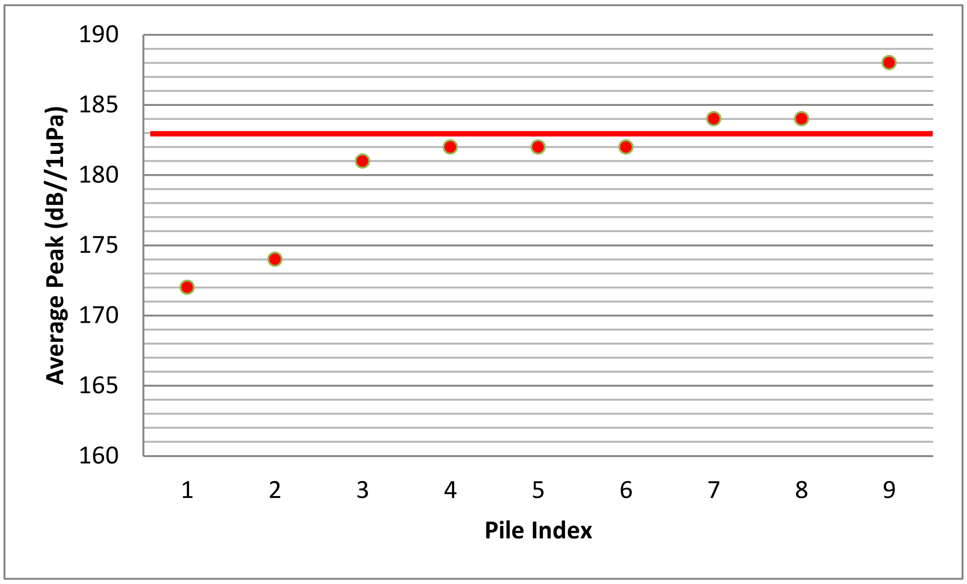

Figure B-19. Concrete 16, 18-inch Average Peak Measurements

Figure B-20. Concrete 24-inch Average Peak Measurements

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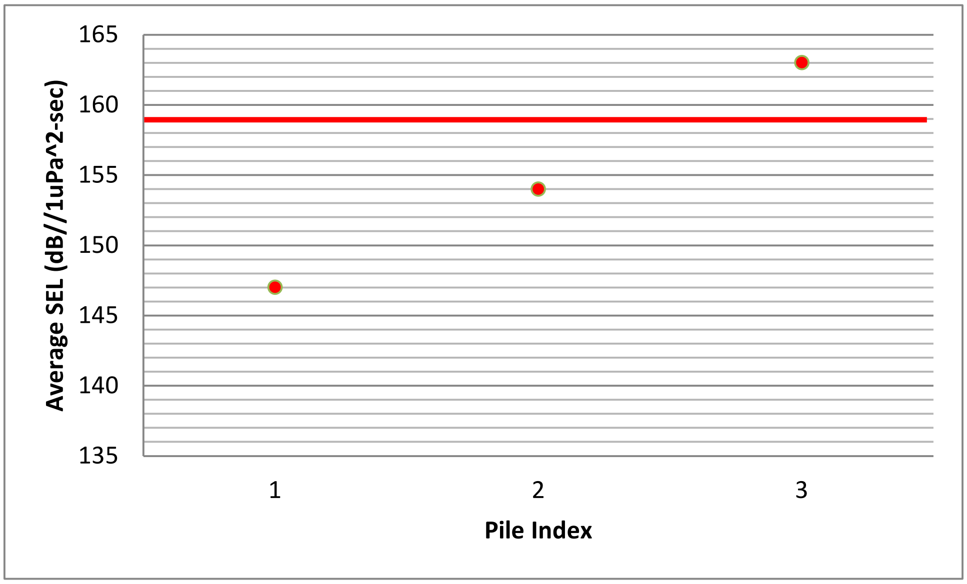

Figure B-21. Concrete 16, 18-inch SEL Measurements

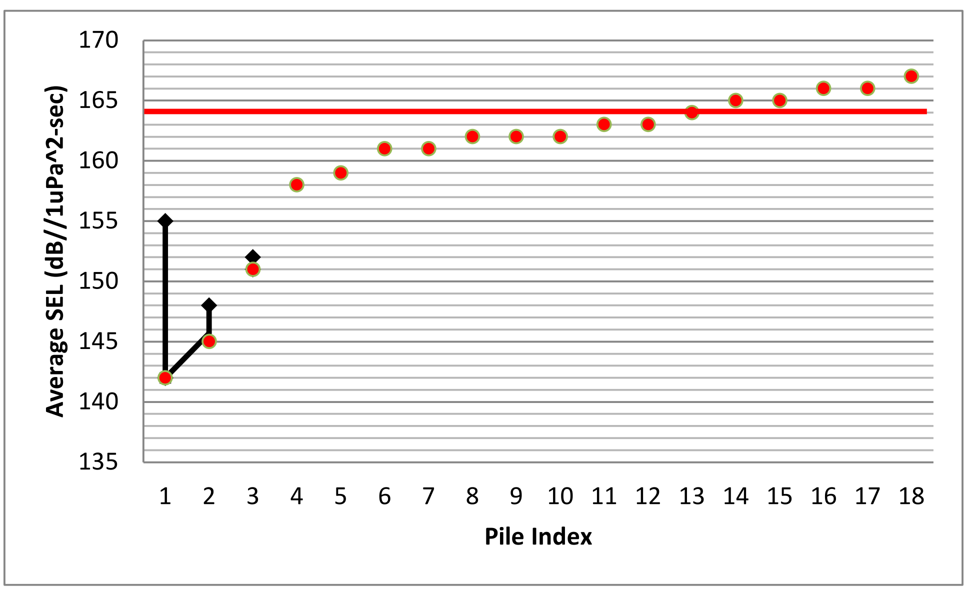

Figure B-22. Concrete 24-inch SEL Measurements

Proxy Source Sound Levels and Bubble Curtain Attenuation
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Vibratory RMS

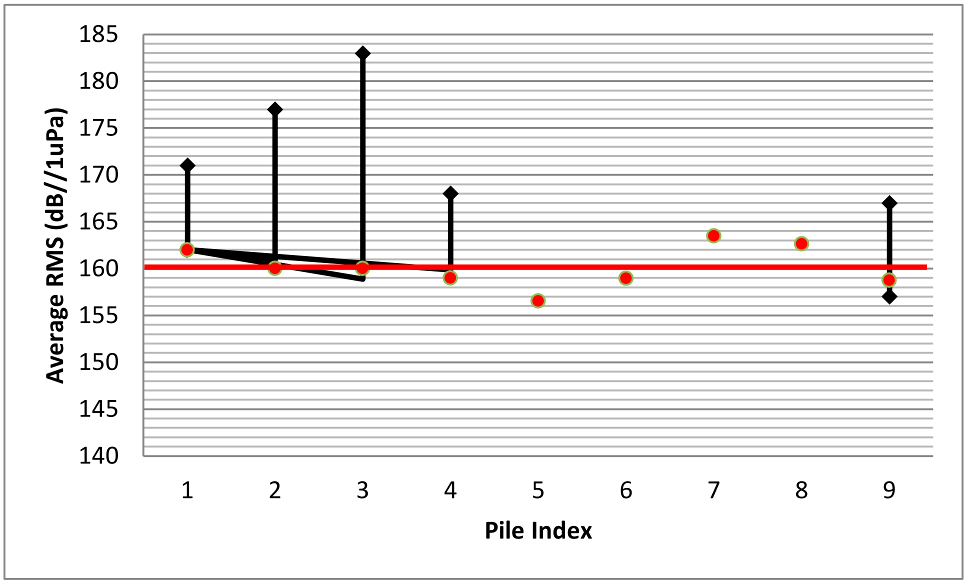

Figure B-23. 24-inch RMS Vibratory Measurements

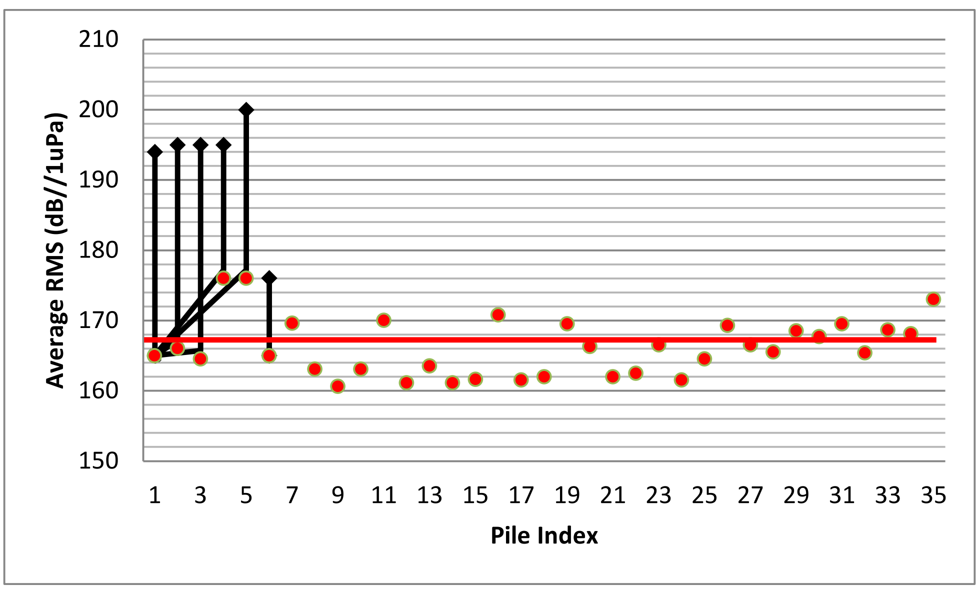

Figure B-24. 30-inch RMS Vibratory Measurements

Proxy Source Sound Levels and Bubble Curtain Attenuation
Revised January 2015

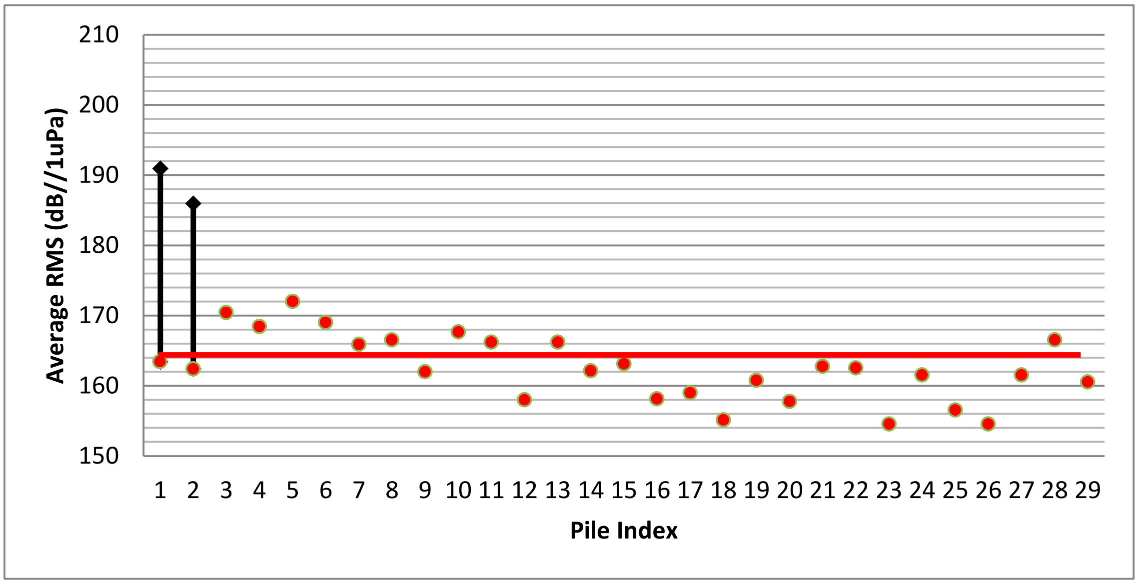

Figure B-25. 36-inch RMS Vibratory Measurement

Proxy Source Sound Levels and Bubble Curtain Attenuation
Revised January 2015

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