Underwater Noise Reduction of Marine Pile Driving Using a Double Pile: Vashon Ferry Terminal Test

WA-RD 861.1

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UNDERWATER NOISE REDUCTION OF MARINE PILE DRIVING USING A DOUBLE PILE
Vashon Ferry Terminal Test

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16. ABSTRACT

Impact pile driving of steel piles in aquatic environments produces extremely high underwater sound levels. To address this problem, a double-walled pile has been developed to decrease the total noise transmitted into the water and substrate. The double-walled pile consists of two concentric steel pipe piles flexibly connected by a special driving shoe, allowing for an air gap between the two tubes. The double-walled pile is driven into the sediment by using traditional equipment that strikes the inner pile only. The air gap between the inner and outer pile and the flexible coupling prevent the radial deformation wave produced by the pile hammer from interacting with the water and the sediment.

A second full-scale test of the double-walled pile technology was performed at Vashon Island, Puget Sound, Washington. A potential reduction of the peak pressure in excess of 17dB was observed for the double pile and of 16 dB for the mandrel pile. Root mean square (RMS) levels and cumulative sound exposure levels (SEL) decreased by 13 dB and 12 dB, respectively. Use of the WSDOT Geotechnical Design Manual Pile Driving Formula showed that the pile capacity of the novel piles was comparable to that of a control pile with the same outer diameter.

PDA (Pile Driving Analyzer) data were also collected from both the inner and outer piles of the mandrel and double piles and will be used to modify current software for predicting drivability and stresses in the piles (WEAP (Wave Analysis of Pile Driving) analysis) and for estimating load capacity after driving (CAPWAP (Case Pile Wave Analysis Program) analysis).

17. KEY WORDS
Pile, sound, acoustic, attenuation, marine, pressure, SEL, sound exposure level, sediment, Mach wave

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DISCLAIMER

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Executive Summary

Impact pile driving of steel piles in aquatic environments produces extremely high underwater sound levels. It has been shown that current pile driving noise attenuation techniques, such as bubble curtains and cofferdams, provide variable noise reduction due to the unconstrained propagation of Mach sound waves [1] directly from the sediment surrounding these attenuation devices into the water.

To address this problem, a double-walled pile has been developed to decrease the total noise transmitted into the water and substrate. The double-walled pile consists of two concentric steel pipe piles flexibly connected by a special driving shoe, allowing for an air gap between the two tubes. The double-walled pile is driven into the sediment by using traditional equipment that strikes the inner pile only. The air gap between the inner and outer pile and the flexible coupling prevent the radial deformation wave produced by the pile hammer from interacting with the water and the sediment. In one embodiment of the double-pile design the inner tube can be removed and repeatedly reused.

A second full-scale test of the double-walled pile technology was performed at Vashon Island, Puget Sound, Washington. A reduction of the peak pressure in excess of 13 dB was measured for the double and the mandrel piles at a range of approximately 10 m. Tests showed a reduction in root mean square (RMS) levels of >9 dB and in cumulative sound exposure levels (SEL) of >7 dB. Unanticipated steel-to-steel contact with an installed template during the entire driving process decreased the sound attenuation performance of the double-walled piles.

When the data were filtered in an attempt to remove the effect of the steel-to-steel contact with the template, then reductions of the peak pressure in excess of 17dB for the double piles and 16 dB for the mandrel piles were observed. The RMS levels and cumulative SEL showed reductions of approximately 13 dB and 12 dB, respectively.

An additional problem caused by the template was that the effectiveness of a bubble curtain could not be determined because the template prevented deployment of a bubble curtain around the single-walled pile during the test.

By using the WSDOT Geotechnical Design Manual Pile Driving Formula, the researchers estimated that the pile capacity of the novel piles was comparable to that of a control pile of the same outer diameter.

1 INTRODUCTION

Impact pile driving of steel piles in marine environments produces extremely high sound levels in the water. Numerous studies have shown current noise attenuation techniques are costly and provide limited or variable noise reduction [1-3]. This is because the noise from pile driving is transmitted through the sediment back into the water column [1, 4-8]. In several publications [1,6,7], we showed that the primary source of underwater sound from an impact driven pile originates from radial expansion of the pile as a compression wave propagates down the pile after each strike. This supersonic (with respect to the water) radial expansion wave produces an acoustic field in the shape of an axisymmetric cone [1], or Mach cone (Figure 1).

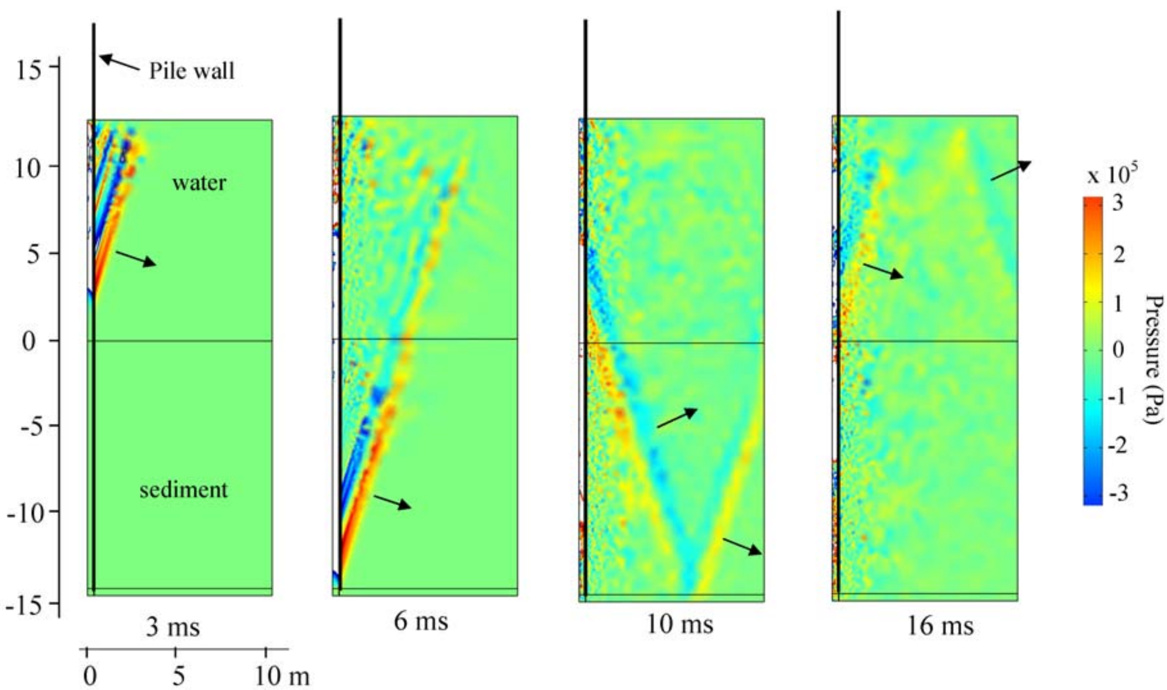

Figure 1: Acoustic pressure surface plots showing the acoustic radiation from the pile at 3, 6, 10, and 16 ms after impact by pile hammer. The propagation direction of the wave front associated with the Mach cones produced in the water and the sediment is indicated by the arrows.

We showed that the ability of any sound shield that surrounds the pile in the water only is limited by the fact that an upward moving reflected Mach sound wave is produced in the sediment and is transmitted back into the water [1,6]. Figure 2 illustrates how sound from the seabed leaks out from the sediment, limiting the effect of the surrounding bubble curtain.

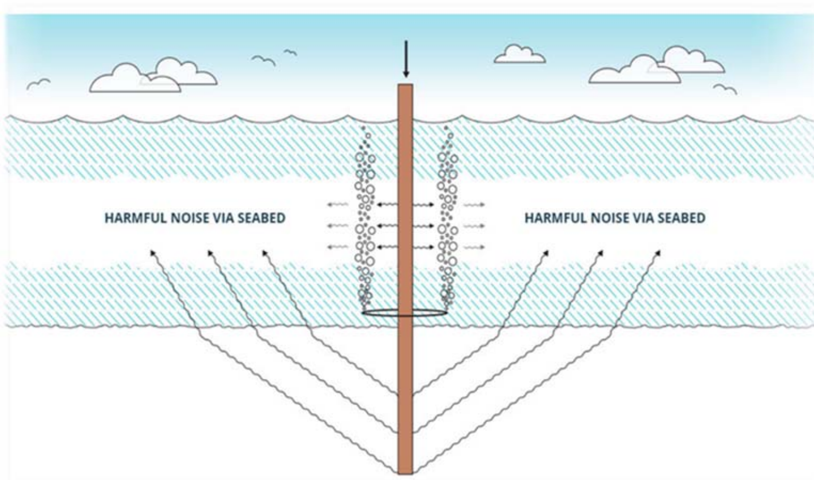

Figure 2: Illustration of how sound from the seabed is transmitted unhindered by a sound shield surrounding the pile in the water, e.g., a bubble curtain.

2 BACKGROUND

Underwater noise created by impact pile driving can reach sound levels that have deleterious effects on aquatic wildlife [9-14]. Because of the critical state of many animal populations, the U.S. Fish and Wildlife Service and National Oceanic and Atmospheric Administration have established underwater noise thresholds (in terms of sound exposure level (SEL) and root mean square (RMS)) to facilitate analysing impacts to underwater fauna (Table 1).

Table 1: Underwater noise thresholds for critical species in the Pacific Northwest

	Injury Threshold	Non-Auditory Injury Threshold	Disturbance Threshold
MARBLED MURRELETS (Diving Birds)	202 dB $_{SEL}$	208 dB $_{SEL}$	N/A
CETACEANS (Whales, Porpoises)	180 dB $_{RMS}$	N/A	160 dB $_{RMS}$
PINNIPEDS (Seals, Sea Lions)	190 dB $_{RMS}$	N/A	160 dB $_{RMS}$
FISH (≥ 2 Grams)	187 dB $_{SEL}$	N/A	150 dB $_{RMS}$
FISH (< 2 Grams)	183 dB $_{SEL}$	N/A	150 dB $_{RMS}$
FISH (All Sizes)	206 dB $_{Peak}$		

Our previous and other research has shown that without containing both the water and the sediment borne noise, larger steel pipe piles cannot be installed via impact hammer without exceeding the established underwater noise thresholds. Impact driving of small steel piles may remain below some of the established thresholds.

The double-walled pile concept was developed to comprehensively address noise from marine pile driving directly in the water and reflecting from the sediment. It was tested extensively through finite element modeling, sub-scale testing, and full-scale testing [6, 7]. For a detailed description of the double-walled pile concept, design, and first field test results, please refer to WSDOT Report WA-RD 849.1 [7]. For completeness, the noise attenuation results for the double pile and the mandrel pile from our first field test in soft sediment are shown in Figure 3.

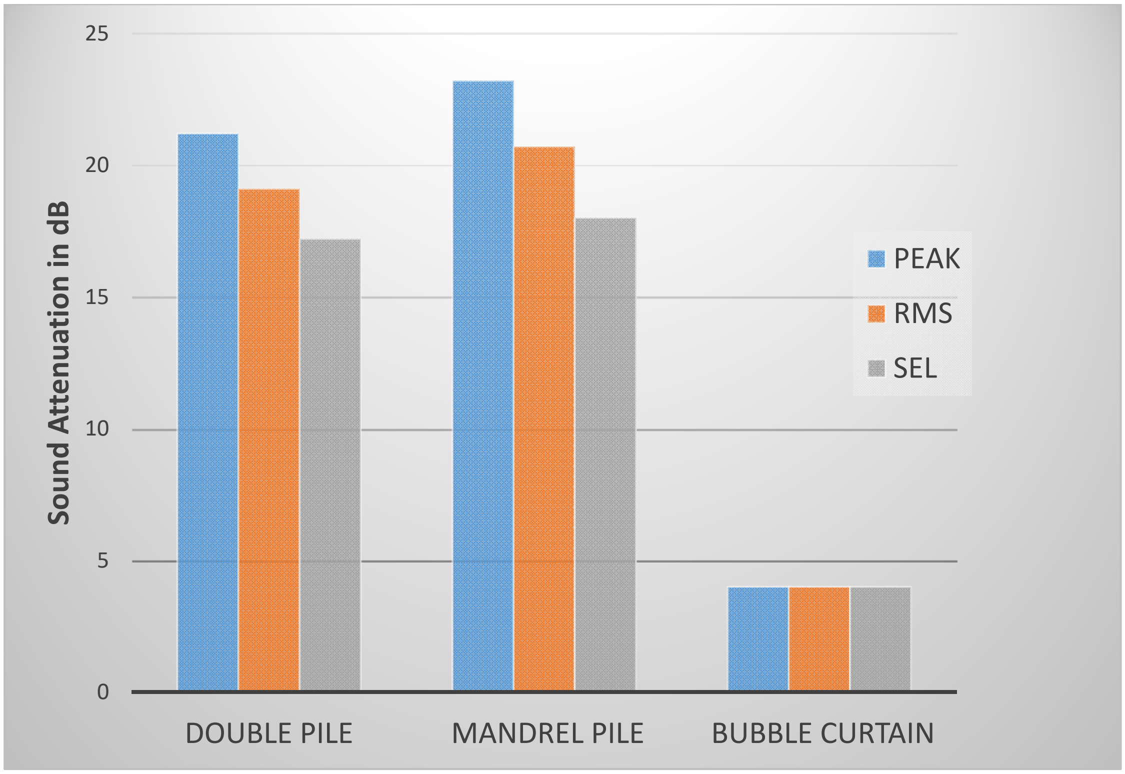

Figure 3. Summary of the results for the first field test for underwater sound reduction in terms of SEL, RMS, and Peak pressure for the double-walled test pile and the mandrel test pile relative to the control pile at a range of approximately 8 meters (from WSDOT Report WA-RD 849.1).

3 SECOND FULL-SCALE FIELD TEST

After the success of these earlier tests, a second full-scale field test was completed to evaluate the drivability of the double-walled pile and mandrel pile. The same three piles that were tested in soft sediment at Commencement Bay were tested at the Vashon Island Ferry terminal (Figure 4). The outer diameter of the single wall control pile was 0.765 m (30 inch) with a wall thickness of 19 mm (0.75 inch). The outer and inner piles in the double-walled pile had an outer diameter of 0.765 m and 0.610 m (24 inch), respectively. The wall thickness of the outer pile was 19 mm (0.75 inch). The wall thickness of the inner pile was 16 mm (0.625 inch). The length of the piles was 23 m (76.5 ft).

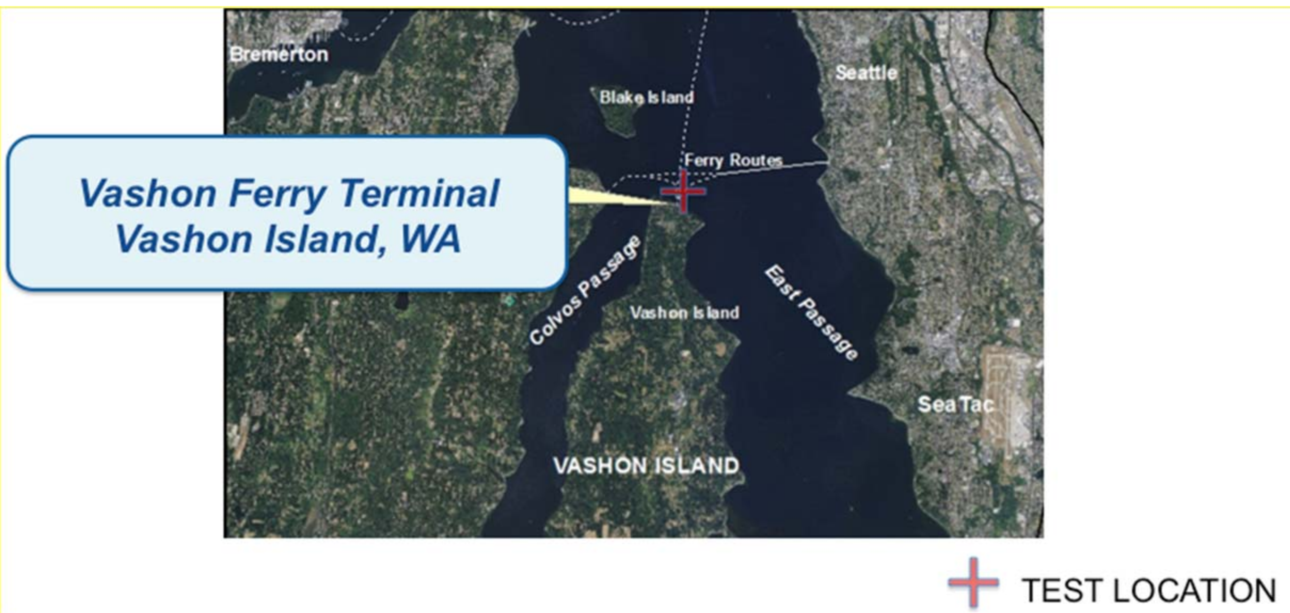

Figure 4: Vashon Ferry Terminal test site.

The hammer used during the test was an APE Model D80-23, single-acting, diesel impact hammer with a ram weight of 17,620 lb. The construction barge complex was positioned approximately 500 m offshore and 30 m from the ferry terminal pier in ~8m of water. The contractor installed a driving template consisting of a lattice of steel I-beams affixed to six 24-inch-diameter steel piles. Each of the test piles was chained to the template before initiation of driving. No rubber bumpers were attached to the inside face of the lattice openings to prevent steel-to-steel contact between the piles and the template.

Piles were installed on December 7 and 8, 2015. The single-walled (control) pile was installed on December 7th, beginning approximately at noon, with a short duration of driving, after which dynamic instrumentation was affixed to the pile, followed by a longer period. The pile was driven to a penetration of 39 ft. Driving of the double-walled pile began at approximately 2:50pm and reached a penetration of 40 ft in three phases. The mandrel driven pile was driven on December 8th, beginning at approximately 12:45pm, in one phase, to a penetration of 37 ft.

3.1 Test Preparation

This section briefly describes the preparations required to get the previously used piles ready for the second test, the full-scale test site (location, considerations for choosing the site, and site characteristics), and acoustic monitoring planned for the test.

3.1.1 Pile Refurbishing

Before the second test on Vashon Island, the pile tips or driving shoes were separated from the pilings and dismantled to evaluate wear from the previous test at Commencement Bay and to ensure they were properly functioning for the impending test. The internal components and the polymer flexible couplings of the pile tips were in excellent condition from the previous test. As a result, the components were simply rinsed with fresh water and then put back together for reuse in the Vashon test.

3.1.2 Pile Fabrication

Quigg Brothers, the construction contractor for the Vashon Ferry Terminal project, was provided with a standard 76.5-ft-long control pile, a fully fabricated 76.5-ft-long double-walled pile, and a partially fabricated 76.5-ft-long mandrel pile. In the latter, the outer pile and driving shoe had been welded together, but the mandrel had not yet been inserted into the outer pile. Figure 5 depicts the lofting of the fully fabricated double-walled pile into the driving template.

Figure 5: Crane lofting double-walled pile into place. Photo courtesy Jim Laughlin, WSDOT.

Rather than inserting the mandrel into the outer pile at the storage yard, Quigg Brothers opted to insert the mandrel on-site at the Vashon Test location. Figure 6 depicts the insertion of the mandrel pile into the outer pile.

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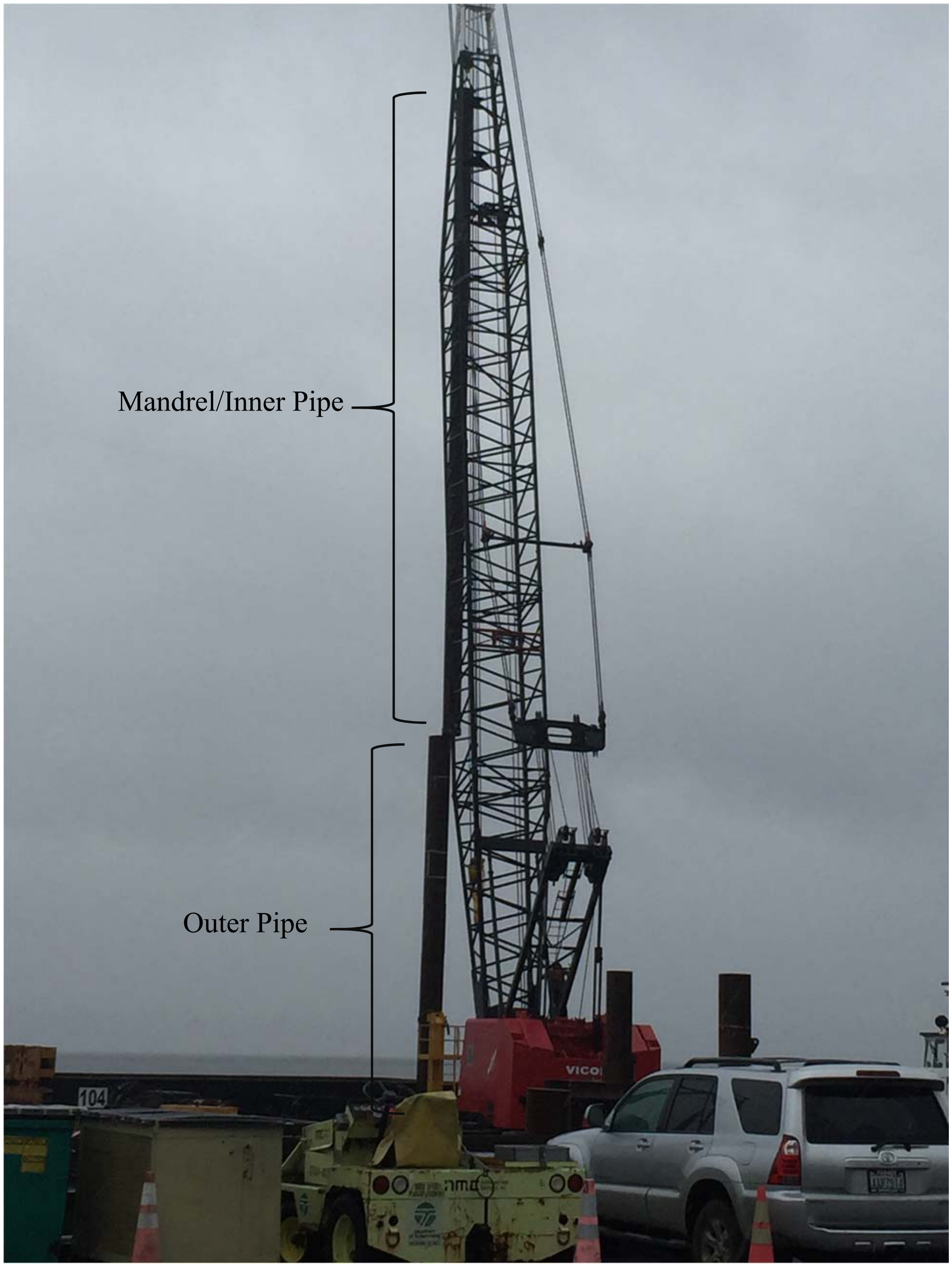

Figure 6: Crane lofting mandrel into place. Photo courtesy Jim Laughlin, WSDOT.

3.1.3 Test Location and Geotechnical Considerations

The test was located along the northeast shore of Vashon Island (Figure 4). This location was chosen because it provided a limited depth to bearing soil layer (allowing for a relatively short test pile length), and it provided a water depth of approximately 8 m at the test piles (allowing for uninterrupted noise transmission). In addition, the site represented moderately hard substrate conditions, which are prevalent throughout the region.

3.1.4 Predicted Monitoring and Exclusion Zone Calculations

As part of the permitting requirements for the Vashon Ferry Terminal project as a whole, Washington State Ferries estimated the extent of potential injury to marine mammals and other protected species associated with all pile driving activities on the basis of the background underwater sound levels, anticipated noise levels associated with pile driving, assumed noise attenuation, and accepted regulatory thresholds. The test pile project constituted one component of this larger project. For the Marine Mammal Protection Act Incidental Harassment Authorization application, Washington State Ferries calculated the Zones of Impact (ZOI) and Zones of Exclusion (ZOE) for impact driving associated with test pile activities. These areas are significant in that they define the areas within which effects to protected species require federal authorization and also on-site monitoring during pile driving activities.

For these calculations, WSF assumed a bubble curtain would provide an 8- to 10-dB reduction for impact driving of 30-inch steel test piles, resulting in a worst-case noise level of 179 to 181 dB RMS (189-10/8) at 16 m.

Using the NOAA/NMFS practical spreading loss model, WSF predicted the following:

- the 190 dBRMS pinniped injury threshold would be reached within 4.0 m/13 ft.
- the 180 dBRMS cetacean injury threshold would be reached within 19 m/62 ft.
- the 160 dBRMS harassment threshold would be reached within 402 m/1,319 ft. = ZOI-4.

The more conservative cetacean injury zone (19 m/62 ft.) was used to set the 30-inch steel ZOE where active biological monitoring would be required during impact pile driving. The 30-inch steel impact ZOE and ZOI (excluding land) are shown in Figure 7 for one representative pile.

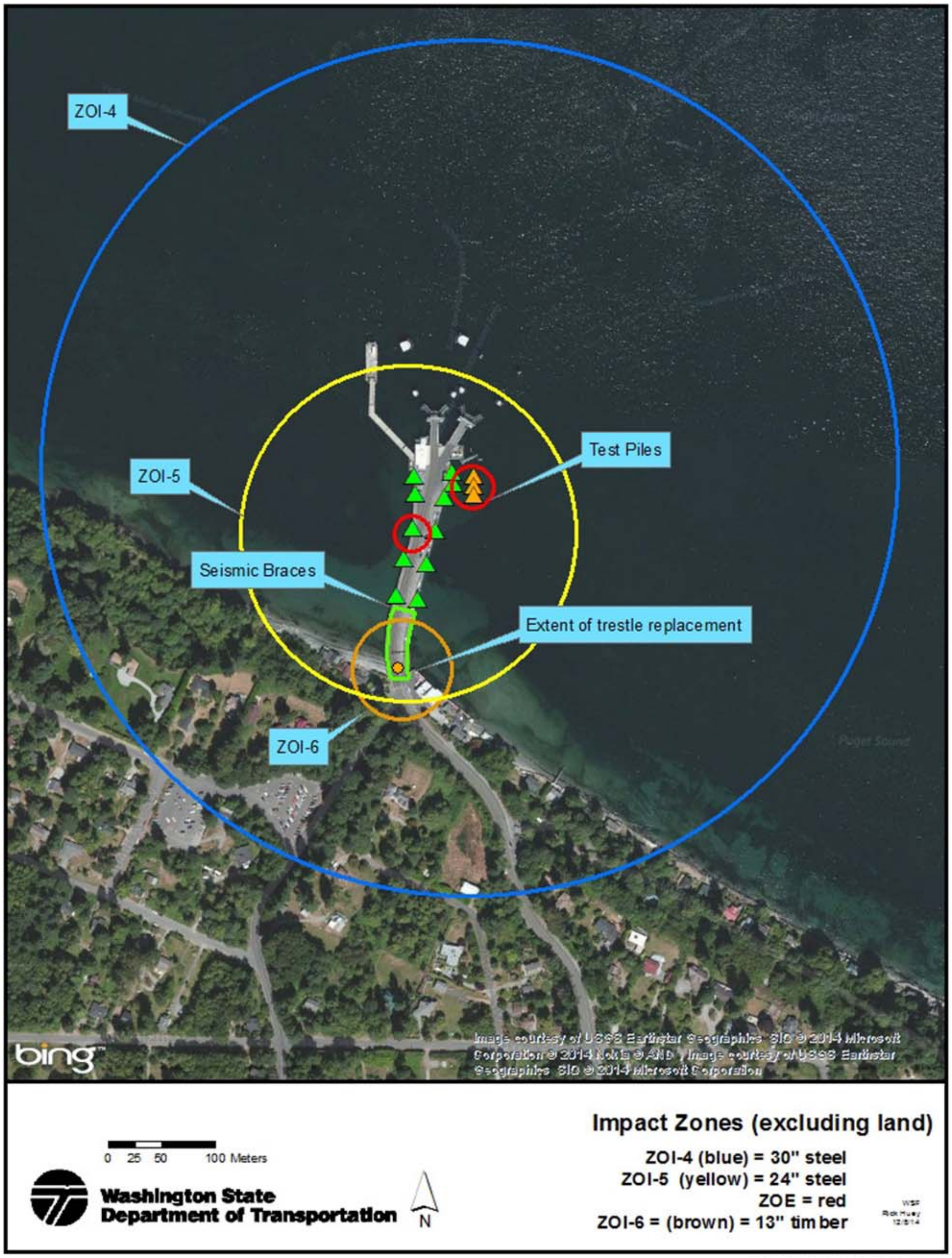

Figure 7: Zones of impact and exclusion for pile driving activities.

Similarly, for Endangered Species Act compliance, WSF calculated distances to thresholds for other protected species. These calculations are summarized below.

Using the NOAA/NMFS practical spreading loss model, WSF predicted the following:

- the 208 dB SEL barotrauma threshold for murrelet is reached within 11 m/36 ft.

- the 202 dB SEL auditory injury threshold or marbled murrelet would be reached within 29 m / 95 ft.
- the 206 dB peak injury threshold for fish would be reached within 30 m/98 ft.
- 183 cumulative SEL dB injury threshold for fish <2g would be reached within 527 m/1729 ft.
- The 187 cumulative SEL dB injury threshold for fish >2g would be reached within 285 m/935 ft.
- The 150 dBRMS fish behavior would be is reached within 6370 m/20,899 ft.

3.1.5 Acoustic Monitoring

Figure 8 provides an overview of the location of the vertical line array (VLA) (yellow dot) and the single WSDOT hydrophone (blue dot) relative to the test piles. The measurements for this report were made using a VLA system consisting of five hydrophones with a sensitivity of -211 dB re 1 V/μ and a spacing of 0.7 m. The VLA was placed at a range of approximately 10 m and in a water depth of 5.5 m.

Figure 8: Placement of near-field hydrophones. Blue circle indicates a single WSDOT hydrophone, and the yellow dot indicates a five-hydrophone VLA deployed by the Department of Mechanical Engineering, University of Washington.

3.1.6 Pile Installation

The piles were installed with a standard APE Model D80-23 impact hammer without the use of any special equipment.

3.2 Test Results

3.2.1 Drivability Results

Dynamic measurements were collected through strain sensors and accelerometers attached approximately 5 ft from the top of the piles. The standard configuration of one strain sensor and one accelerometer was used on two diametrically opposing sides of the control pile. For the double pile and mandrel pile, data were collected with this standard configuration for both the inner and outer piles. An eight-channel Pile Driving Analyzer (PDA) system (Pile Dynamics, Inc) was used to collect and analyze the data. The PDA analysis was performed by Robert Miner Dynamic Testing, Inc.

Figure 9 shows a typical strain recording as a function of time for the control pile (blow 50) with a maximum longitudinal strain of approximately 0.1 percent. Figure 9 shows the strain in both the inner and outer piles for the mandrel pile. It can be seen that the maximum strain in the control pile was similar to the strain in the inner pile of the double-walled pile. Note that the hammer only struck the inner pile as the piles were driven into the sediment. The outer piles were connected to the inner pile via a watertight flexible coupling in the driving shoe (Figure 10).

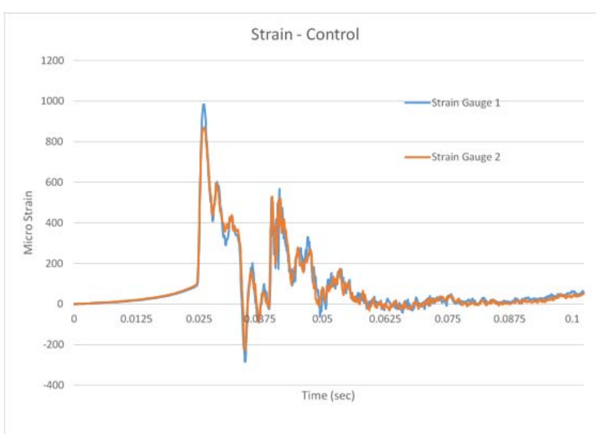

Figure 9. Longitudinal strain in the control pile as measured by the PDA system.

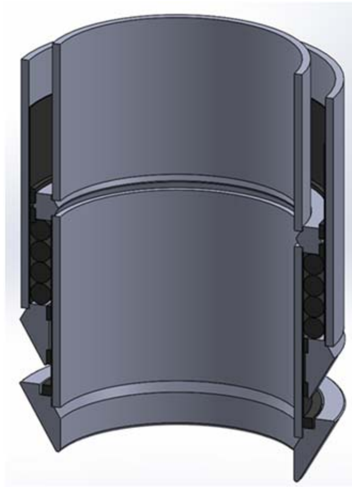

Figure 10. Schematic of how the outer pile was connected to the inner pile via a flexible coupling in the driving shoe.

For a detailed description and function of the driving shoe, please see WSDOT report WA-RD 849.1 [7]. Figure 11 shows the strain between the outer (left) and inner (right) pile for a typical hammer strike. The low acceleration in the outer pile was due to the fact the measurement location was close to the top free end of the pile where the boundary condition was stress and strain free.

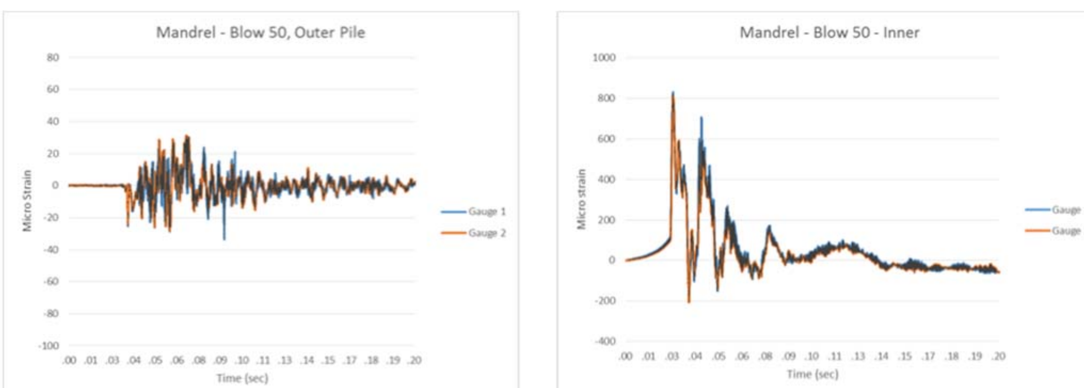

Figure 11. Strain in the outer pile (left figure) and inner pile (right figure) as measured by the installed PDA system

Figure 12 show the displacement produced by a typical hammer strike. The effect of the flexible coupling can be seen in that the displacement of the outer piles lags the displacement of the inner piles. From a drivability standpoint, the test piles required additional blows for the same penetration. This was most likely due to two factors: 1) the bearing surface of the driving shoes of the double and mandrel piles was larger than the driving shoe of the control, and 2) the stiffness of the polymer spring at the bottom end of the double and mandrel piles was too soft for the sediment type. A higher stiffness would have created higher axial peak stresses in the outer pile, making penetration into the sediment against the skin friction easier. Table 2 summarizes the pile driving record with the driving depth and blow counts for each of the piles.

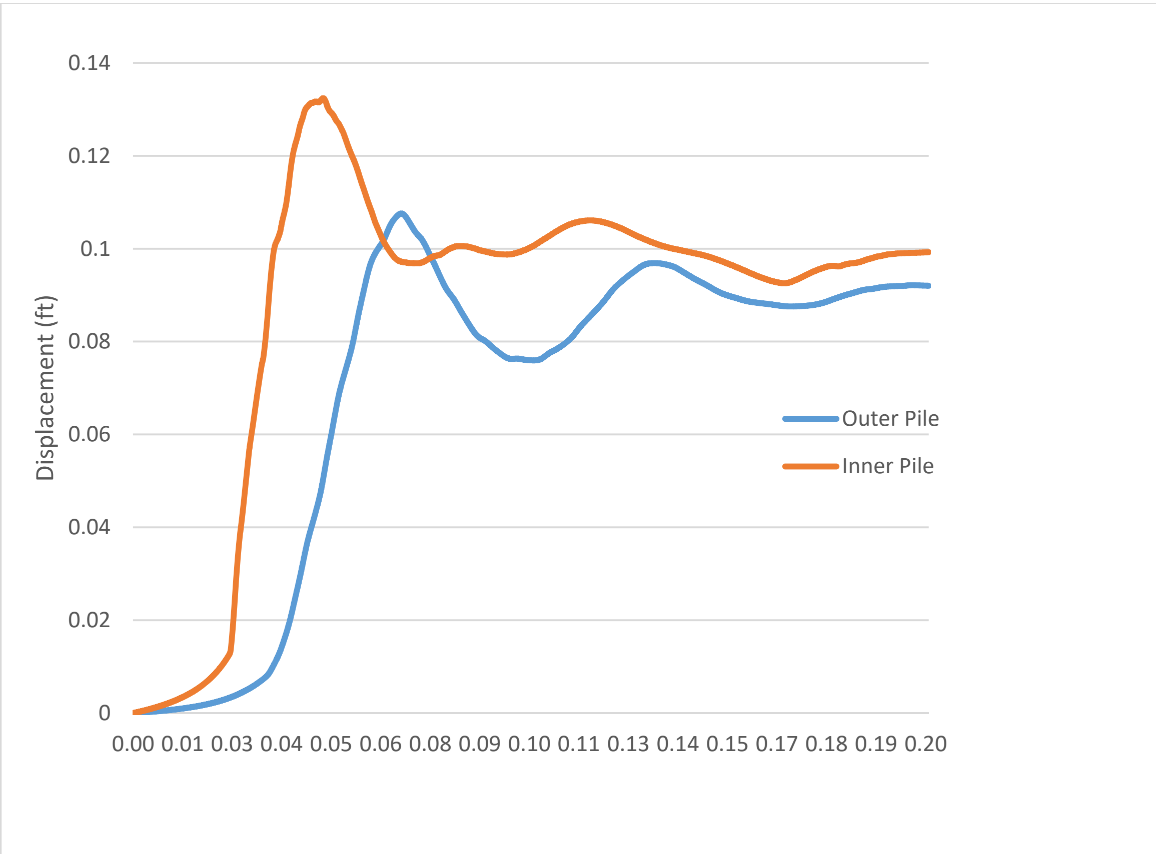

Figure 12. Displacement of the inner and outer pile of the double wall pile after a pile hammer strike (strike 100)

Table 2: Drivability summary

	Penetration	Number of Blows	Blows/Foot (last three feet)	Estimated Ultimate Pile Capacity (kips)
Control	**39**	**290**	**16**	**1318**
Double Pile	**40**	**412**	**18**	**1340**
Mandrel Pile	**37**	**324**	**17**	**1100**

The estimated ultimate pile capacity was estimated by using the WSDOT Geotechnical Design Manual Pile Driving Formula. Note that this formula was developed for a single-walled pile. The listed pile capacity of the double and mandrel piles should therefore not be viewed as accurate. We aim to modify the WSDOT formula to make it applicable to the novel double piles.

The data that PDA collected from both the inner and outer piles of the mandrel and double piles will be used to modify current software for predicting drivability and stresses in the piles (WEAP analysis) and for estimating load capacity after driving (CAPWAP analysis).

3.2.2 Acoustic Results

Two efforts to measure the noise attenuation of the double and mandrel pile were conducted. One was conducted by the Applied Physics Laboratory, University of Washington, and focused on measuring the radiated noise at an approximate range of 100 m. The results of that study are described in a separate WSDOT report. We will here focus on measurements conducted with the VLA at a range of 10 m from the piles.

Figure 13 summarizes the results for underwater noise reduction in terms of CSEL, RMS, and Peak pressure for the double-walled test pile and mandrel test pile relative to the control pile. We found two factors that decreased the sound attenuation during this field test in comparison to the first test at Commencement Bay. First, the sound attenuation of the double-walled piles was found to be limited by steel to steel contact with the installed pile-driving template. The steel-to-steel contact transferred the vibratory motion of the outer pile to the entire template, resulting in amplified noise radiation into the water. Second, the flexible coupling that worked very well during the first test in soft sediment was reused and found not to work as well during the second test. The harder sediment at the second trial compressed the polymer rings in the flexible coupling cavity to the point that the radial swelling of the polymer cased the top polymer ring to be partially squeezed out of the cavity. This excessive deformation took place in both the double pile and the mandrel pile and was discovered during examination of the couplings after the piles had been extracted and separated from the driving shoes.

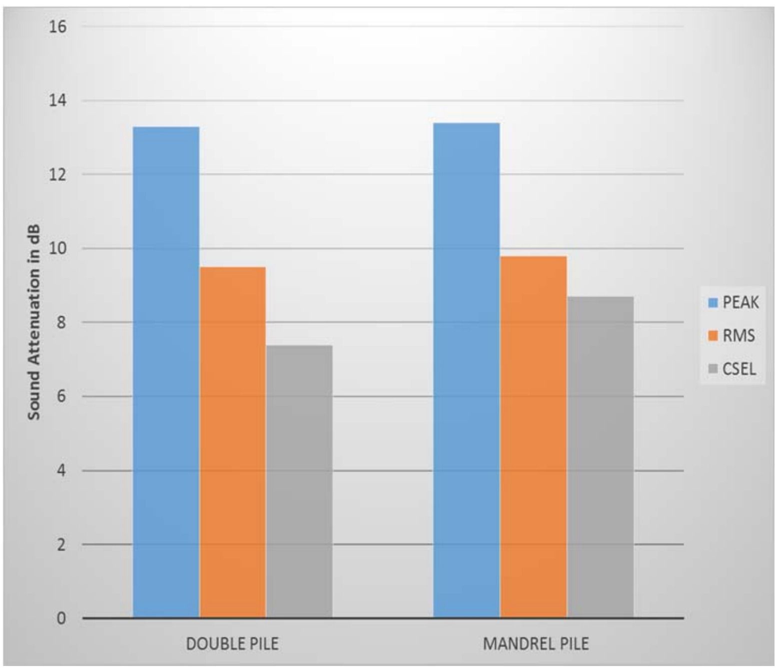

Figure 13. Summary of sound reduction in terms of CSEL, RMS and Peak pressure for the double-walled test pile and mandrel test pile relative to the control pile at a range of 10 m. Averaged over depth and not filtered to correct for template/pile contact.

The excessive deformation of the polymer coupling created a path for the noise to be transferred from the inside pile wall to the outside wall and subsequently the water and the template. Stiffer polymer rings in both the double and mandrel piles would have prevented this from taking place, which in turn would have led to a higher sound attenuation of the piles.

The sound attenuation shown in Figure 13 depicts measured sound levels. No attempt to remove the added noise from the template and the coupling chamber wall was made. A reduction of the peak pressure in excess of 13 dB was measured for the double and the mandrel piles. Measurements also showed a reduction in RMS levels of >9 dB and in cumulative SEL of >7 dB.

To estimate the effect of the template, we compared the frequency content of the piles during the first field test in Commencement Bay, where no template was used, with the frequency of the second field test, where the steel-to-steel contact with the template was present. We saw resonance peaks at approximately 75 Hz and 180 Hz with the template that we did not see during the test in Commencement Bay. Because the same piles were used for both tests, we can reasonably conclude that these two additional resonances were due to the template.

Figure 14 summarizes the noise reduction in terms of CSEL, RMS and Peak pressure after the data from all three piles were high-pass filtered using a FIR filter to remove the 75 Hz peak to partially correct for the direct contact with the driving template. A reduction of the peak pressure in excess of 17dB was observed for the double pile and in excess of 16 dB for the mandrel pile. The RMS levels decreased approximately 13 dB and cumulative SEL decreased by 12 dB. Note that the attenuation would most likely have been greater if the effect of the template could have been completely removed (not just its lowest resonance peak).

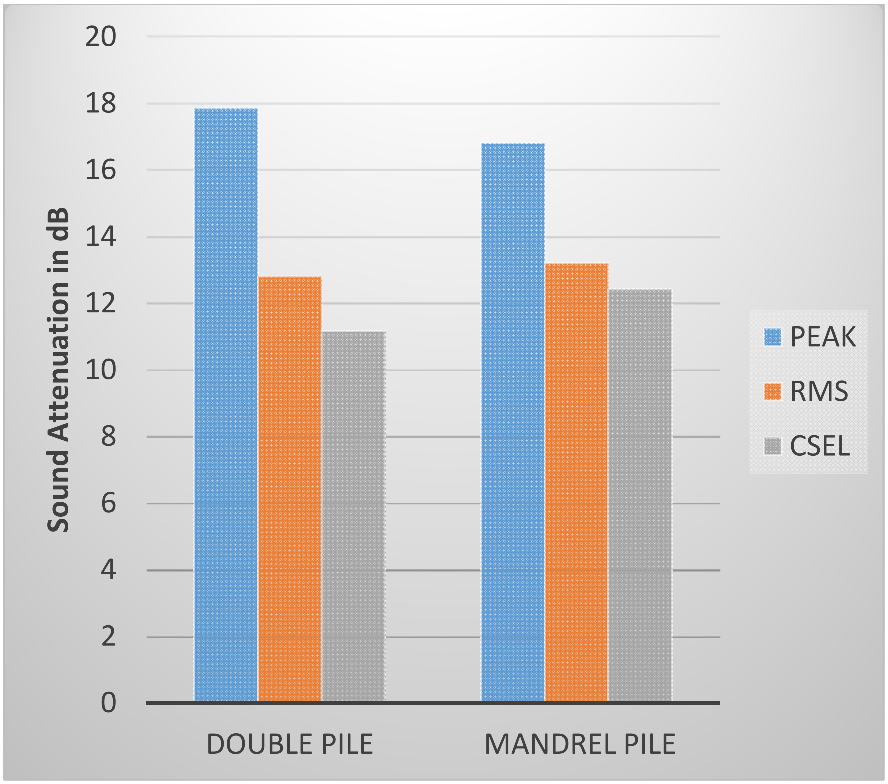

Figure 14. Summary of sound reduction in terms of CSEL, RMS and Peak pressure for the double-walled test pile and mandrel test pile relative to the control pile at a range of 10 m. Averaged over depth and filtered to partially correct for template/pile contact.

In comparison to existing biological thresholds that currently inform the regulations of underwater noise relative to disturbance and potential injury to sensitive species, the noise generated by impact installation of the standard control pile exceeded all but one (murrelet non-auditory, see Table 3) of the established thresholds, whereas the test piles largely fell below them.

Table 3 summarizes noise levels, filtered to correct for the effect of the template, at a range of approximately 10 meters in comparison to established biological thresholds. The single-walled control pile exceeded six of the seven thresholds listed in the table. In contrast, sound levels from the double-walled pile and mandrel pile were below five of the seven thresholds and therefore would avoid or minimize associated impacts to sensitive species. The sound levels in RMS indicated exceedance of disturbance thresholds for cetacean/pinniped species, and in cumulative SEL, exceedance of the dual fish injury thresholds within 10 meters of the double-walled and mandrel pile.

Table 3: Measured values vs. thresholds

The measured values were filtered to correct for the effects of the template, as described above.

	Mandrel	Double Wall	Single Wall (Control)	FISH	CETACEAN INJURY	CETACEAN / PINNIPED DISTURBANCE	PINNIPED INJURY	MURRELET INJURY	MURRELET NON-AUDITORY
PEAK	198.0	196.9	214.8	206	-	-	-	-	-
$RMS_{90\%}$	177.0	177.5	190.4	-	180	160	190	-	-
CSEL	192.7	193.9	205.1	187 / 183	-	-	-	202	208

Noise reduction provided by the double pile also reduced the size of the monitoring zone required to assess potential harassment and injury to sensitive marine wildlife. The area potentially ensonified to a sound level exceeding the thresholds shrunk dramatically, as shown by a comparison of noise levels associated with the control pile and the double-walled and mandrel pile, described below and shown in Figure 14.

The ZOI and ZOE for the control pile was recalculated to reflect filtered noise levels (190 dB RMS) at 10 m and the fact that the bubble curtain could not be deployed with the pile driving template in place. Thus the actual worst case noise levels for impact driving of the 30-inch steel control pile was as follows using the NOAA/NMFS practical spreading loss model:

- the 190 dBRMS pinniped injury threshold would be reached within 11 m/35 ft.
- the 180 dBRMS cetacean injury threshold would be reached within 49 m/162 ft.
- the 160 dBRMS harassment threshold would be reached within 1,063 m/3,488 ft.

The more conservative cetacean injury zone (49 m/162 ft.) would reflect the ZOE for impact driving of 30-inch steel piles. The ZOI would extend 1,063m/3,488 ft from the impact test pile driving activities.

The other impact areas associated with the 30-inch steel control pile would be as follows:

- the 208 dB SEL barotrauma threshold for murrelet would be reached within 641 m/2,103 ft.

- the 202 dB SEL auditory injury threshold or marbled murrelet would be reached within 1,609 m/5,278 ft.
- the 206 dB peak injury threshold for fish would be reached within 39 m/127 ft.
- the 183 cumulative SEL dB injury threshold for fish <2g would be reached within 29 km/18 mi.
- 187 cumulative SEL dB injury threshold for fish >2g would be reached within 16 km/9 mi
- 150 dBRMS fish behavior threshold would be reached within 5 km/3 mi

The worst case noise levels for impact driving of the 30-inch steel double-walled or mandrel pile would be as follows using the NOAA/NMFS practical spreading loss model:

- the 190 dBRMS pinniped injury threshold would be reached within 1 m/5 ft for the double-walled pile and 1 m/4.5 ft for the mandrel pile.
- the 180 dBRMS cetacean injury threshold would be reached within 7 m/22 ft for the double-walled pile and 6 m/21 ft for the mandrel pile.
- the 160 dBRMS harassment threshold would be reached within 147 m/482 ft for the double-walled pile and 136 m/ 446 ft for the mandrel pile.

The more conservative cetacean injury zone (7 m/22 ft.) would reflect the ZOE for impact driving of 30-inch double-walled piles, and 6 m/21 ft.) would reflect the ZOE for mandrel piles. The worst case ZOI would extend 147 m/482 ft from the impact test pile driving activities for double-walled piles and 136 m/446 ft for mandrel piles.

The approximate radius of the exclusion zone for the control pile (yellow) was 49 m and for the double-walled piles (orange) was 7 m (or 6 m for the mandrel piles) (Figure 14). This smaller zone presents a concomitant reduction in the probability that sensitive species would travel through or be inside this smaller area, which in turn means less risk of potential impacts to marine species and less potential for work stoppage. Similarly, the impact area surrounding the pile would shrink from a distance of 1,063 m to a distance of 147 m for the double-walled piles and to 136 m for the mandrel piles (Figure 15).

Similarly, using the practical spreading loss model, the double-walled or mandrel pile would result in smaller impact areas for other protected species:

- the 208 dB SEL barotrauma threshold for murrelet would be reached within 115 m/377 ft for the double-walled pile and 95 m/312 ft for the mandrel pile.
- the 202 dB SEL auditory injury threshold or marbled murrelet would be reached within 288 m/945 ft for the double-walled pile and 240 m/787 ft for the mandrel pile.
- the 206 dB peak injury threshold for fish would be reached within 2 m/7 ft for the double-walled pile and 3 m/10 ft for the mandrel pile.
- the 183 cumulative SEL dB injury threshold for fish <2 g would be reached within 4.4 km/2.7 mi for the double-walled pile and 5.3 km/3.3 mi for the mandrel pile.
- the 187 cumulative SEL dB injury threshold for fish >2 g would be reached within 2.3km/1.4mi for the double-walled pile and 2.8 km/1.7 mi for the mandrel pile.
- the 150 dBRMS fish behavior threshold would be reached within 681 m/2,234 ft for the double-walled pile and 631 m/2,070 ft for the mandrel pile.

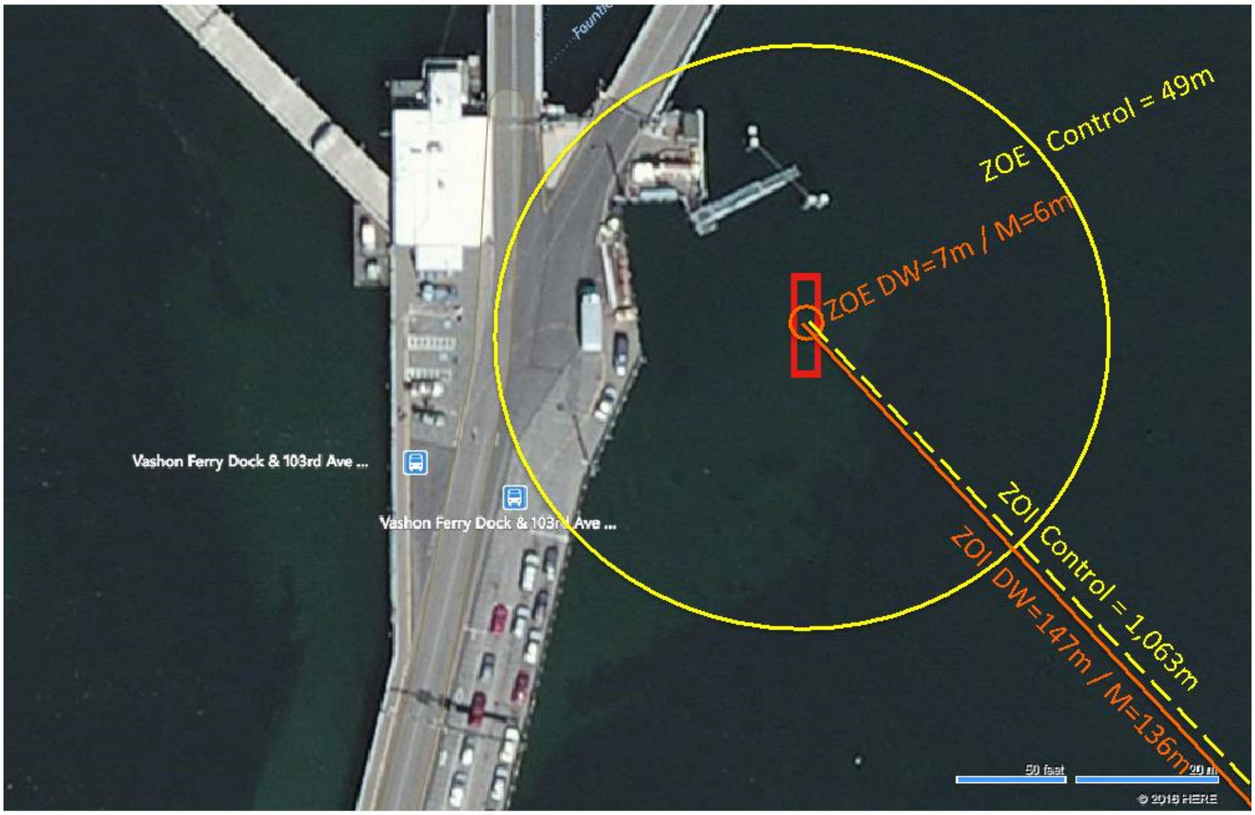

Figure 15. Comparison of monitoring zones.

Table 4 juxtaposes the impact distances or isopleths to each of the biological thresholds discussed above for the control, double-walled, and mandrel piles. The ZOE and ZOI distances appear in the blue highlighted columns.

Table 4. Summary of distances to thresholds

	Fish 206 dB PEAK	Fish 183 dB CSEL	Fish 187 dB CSEL	Cetacean Injury 180 dB RMS (ZOE)	Cetacean / Pinniped Disturbance 160 dB RMS (ZOI)	Pinniped Injury 190 dB RMS	Marbled Murrelet Injury 202 dB CSEL	Marbled Murrelet Non-Auditory Injury 208 dB CSEL
Control	39 m	29 km	16 km	49 m	1,063 m	11 m	1,609 m	641 m
Double Wall	2 m	5.3 km	2.8 km	7 m	147 m	1 m	288 m	115 m
Mandrel	3 m	4.4 km	2.3 km	6 m	136 m	1 m	240 m	95 m

4 SUMMARY AND CONCLUSIONS

We present the results from the second full-scale test of a double-walled pile and a mandrel pile at Vashon Island, Puget Sound, Washington. A steel template was used to aid in the placement of the piles, which caused steel-to-steel contact between the template and the piles. It is believed that this caused a reduction of the sound attenuation performance of both the mandrel pile and the double pile. A reduction of the peak pressure in excess of 13 dB was measured for the double and the mandrel piles at a range of approximately 10 m. Measurements showed a reduction in RMS levels of >9 dB and in cumulative SEL of >7 dB.

When the data were filtered in an attempt to remove the effect of the steel-to-steel contact with the template, a reduction of the peak pressure in excess of 17dB was observed for the double pile and of 16 dB for the mandrel pile. The RMS levels and cumulative SEL decreased by approximately 13 dB and12 dB, respectively.

Use of the WSDOT Geotechnical Design Manual Pile Driving Formula showed that the pile capacity of the novel piles was comparable to that of a control pile with the same outer diameter. PDA data were also collected from both the inner and outer piles of the mandrel and double piles and will be used to modify current software for predicting drivability and stresses in the piles (WEAP analysis) and for estimating load capacity after driving (CAPWAP analysis).

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