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Mitigation of Underwater Pile Driving Noise During Offshore Construction: Final Report

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Executive Summary

This report provides the draft final report for the project entitled “Mitigation of Underwater Pile Driving Noise During Offshore Construction (Phase 1).” This work is sponsored by the Department of the Interior, Minerals Management Service (MMS) Engineering & Research Branch under contract no. M09PC00019. This project addresses high level underwater noise generated by pile driving of large monopiles during construction of offshore wind farms. In particular, this work is an analysis effort to establish the relative importance of the three primary transmission paths and to assess the potential effectiveness of several mitigation options.

In summary, Phase 1 was very successful. The objectives of quantifying acoustic transmission paths, and identifying and ranking noise mitigation concepts, were successfully accomplished. The key to this success was development and application of a physics-based model which enables detailed assessment of the acoustic characteristics of pile hammering, structural response, propagation through water, ground, and air, and treatment performance. The Phase 1 results provide a strong basis for proceeding to the design development and prototyping work envisioned in Phases 2 and 3 of this program. A summary of accomplishments follows.

During this project, APS built and implemented a high fidelity acoustic model of underwater noise produced by driving large piles. A large set of configurations were analyzed, including:

1. 15m and 30m water depth (with the corresponding effect on pile dimensions).
2. Treatment options including: no treatment; several options of compliant layer on the pile; several options of bubble screen, and a dewatered cofferdam modeled as a thick and very rigid structure considered to be an extreme case of the most effective possible treatment.
3. Underwater sound locations near the bottom, in the middle of the water column, near the surface, and an average across depths, all calculated as a function of range.
4. Results at frequencies of 100 to 1000 Hz, which evaluation of existing pile driving noise data indicate is the dominant frequency range.

The results clearly support evaluation of the primary transmission paths and mitigation concept options. Findings regarding the transmission paths can be summarized as follows:

1. The structureborne radiation path dominates underwater noise for nearly all cases.
2. The seismic propagation path is not a significant contributor to underwater noise for the untreated case, where the seismic contribution is 10 to 30 dB below the combination of all paths. The seismic contribution is the limiting factor on the overall effectiveness of treating the structureborne radiation path. With bubble screen or compliant layer treatments, the seismic path becomes a contributing or

occasionally controlling path at a few frequencies. With a dewatered cofferdam installed (the most effective treatment) the seismic path is the controlling path at most frequencies.

3. The airborne transmission path is not a significant contributor to underwater sound in any case. Even with the cofferdam, the airborne path contribution is 50 dB or more below the combination of all paths.

Findings regarding the underwater sound mitigation concept options can be summarized as follows. Note that these predictions are condensed from a large body of information. Specific actual installations will vary in performance, but these predictions are considered to be an effective quantification of relative performance that can be used to support evaluation of potential pile installations and design concept development.

1. A bubble screen is predicted to reduce noise levels by approximately 10 dB. Variation of air volume fraction in the range of 2.5% to 5% does not significantly affect this result.
2. A compliant surface treatment is predicted to reduce noise levels by approximately 10 dB. Varying thickness of the treatment in the range of 2 inches to 8 inches does not significantly affect this result.
3. A massive dewatered cofferdam is predicted to reduce noise levels by approximately 20 dB. This is considered to be the upper bound on possible noise mitigation treatment performance. Model excursions showed no significant difference between cases with the inside of the pile filled with water, air, or mud.

These modeling results provide a basis for evaluating sound mitigation options with respect to specific requirements, such as frequencies and sound levels which have adverse impacts on specific species of marine life found at specific locations a wind farm is to be installed. These specific requirements will yield mitigation performance metrics which will be used for optimization analysis to identify the most feasible and cost effective design. This optimization analysis is a key element of the design development and prototype implementation and evaluation work proposed for Phases 2 and 3.

Additionally, a side study was conducted which indicated that a non-level bottom would not significantly affect these findings.

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1. Introduction

This report provides the draft final report for the project entitled “Mitigation of Underwater Pile Driving Noise During Offshore Construction.” This work is sponsored by the Department of the Interior, Minerals Management Service (MMS) Engineering & Research Branch under contract no. M09PC00019. This project addresses high level underwater noise generated by pile driving of large monopiles during construction of offshore wind farms. In particular, this work is an analysis effort to establish the relative importance of the three primary transmission paths and to assess the potential effectiveness of several mitigation options.

During this project APS built and implemented a high fidelity acoustic elastic/fluid waveguide model of underwater noise produced by driving large piles. A large set of configurations were analyzed in order to address the objectives of this task. The model was created in order to analyze the transfer of power from an axial pile driving force on top of a pile to the surrounding stratified air/water/silt environment. The models captured power radiation through three paths:

Structureborne Radiation: This mechanism concerns sound radiated from the wetted portion of the pile into the water.

Seismic Propagation: This mechanism concerns sound radiated into the ocean bottom from the portion of the pile that is embedded.

Airborne Transmission: This mechanism concerns sound radiated from the “dry” (above the waterline) portion of the pile.

The approach has been developed by refining and extending the Navy-developed Duct Transmission Line (DTL) code. This is a computationally efficient and rigorous approach that provides high fidelity results. It is ideal for “layered” problems, in particular for properly predicting the impact of mitigation treatments which will be manifested as a layer or layers surrounding the monopile. The model has built in algorithms to determine the type and character of acoustic waves generated and how they radiate to the environment for a given input. The model has been refined to properly predict radiation into surrounding fluid (the ocean) as well as ocean bottom (the seismic path).

The waveguide model captured the physics in the nearfield of the pile. Propagation to the farfield was modeled using the OASES code developed by Henrik Schmidt of MIT. OASES is a wavenumber-integral model, which was developed at the SACLANT research center and later at MIT specifically to deal with propagation problems involving both in-water acoustic fields and seafloor seismic fields and has been extensively vetted within the scientific and Naval community. The coupling between the OASES and transmission line models (DTL) was done by replacing the pile with an equivalent array of acoustic and seismic sources in OASES. The amplitudes of these equivalent sources

will be determined by matching DTL and OASES results for the pressure and radial particle velocity outside of the pile, in a least-squares sense. This “virtual source” approach matches the outgoing power across the stratified environment.

Two site water depths were considered: 15m and 30m deep. Nine pile treatment configurations were studied with the transmission line/OASES approach:

1. Bare (untreated) pile (baseline).
2. Bubble screen with 2.5% volume fraction of air.
3. Bubble screen with 5% volume fraction of air.
4. 2 inch thick closed-cell foam isolation layer.
5. 4 inch thick closed-cell foam isolation layer.
6. 8 inch thick closed-cell foam isolation layer.
7. Dewatered cofferdam constructed with a thick steel structure, inside of pile filled with air.
8. Dewatered cofferdam constructed with a thick steel structure, inside of pile filled with water.
9. Dewatered cofferdam constructed with a thick steel structure, inside of pile filled with mud.

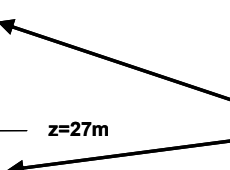
This report provides a detailed summary of the Phase 1 accomplishments.

2. Case Studies: Model Description

2.1. Environment

Available bottom type data for the Mid-Atlantic region were reviewed to identify representative bottom data to be used for the model. The bottom type details are based on the Army Corps of Engineers Draft Environmental Impact Statement (EIS) section 5.1.3.1 and figures 5.1-2 and 5.1-3. Material parameters are based on Hamilton (1980, 1987) (also in Computational Ocean Acoustics table 1.3). The core samples contained many layers of similar acoustic composition. Table 1 summarizes the bottom type parameters used for the model.

Table 1 – Bottom type parameters.

Air		z=0m	
Water	$c_p=1500$ m/s, $\rho=1$ g/cm ³	z=9m	
Sand/Silt	$c_p=1613$ m/s, $c_s=95(z-9)^{0.3}$ m/s, $\rho=1.8$ g/cm ³ , $\alpha_p=0.9$ dB/ λ , $\alpha_s=2.0$ dB/ λ	z=27m	 <p>Note the dependence of shear speed on depth z (in meters)</p>
Sand/Clay	$c_p=1575$ m/s, $c_s=105(z-9)^{0.3}$ m/s, $\rho=1.7$ g/cm ³ , $\alpha_p=0.5$ dB/ λ , $\alpha_s=1.75$ dB/ λ	z=270m	
Bedrock	$c_p=5250$ m/s, $c_s=2500$ m/s, $\rho=2.7$ g/cm ³ , $\alpha_p=0.1$ dB/ λ , $\alpha_s=0.2$ dB/ λ		

One parameter considered in this study was the effect of bottom slope. As discussed below, analysis indicated that a sloped bottom would not significantly affect the relative effectiveness of the noise mitigation treatments, so the calculations were conducted using the assumption of a flat ocean bottom.

2.2. Pile Construction

The Cape Wind Project, a proposed wind farm in Nantucket Sound, is the basis for estimating parameters for monopiles installed in 15m deep water. Figure 1 provides the monopile characteristics used in the model for 15m water depth. European studies for potential installations in deeper water were reviewed to determine representative monopile characteristics for a 30m water depth installation. Figure 2 provides the characteristics of the 30m bottom monopile used in this model.

Note: only lower section of full tower assembly is driven into ocean bottom.

Not to scale

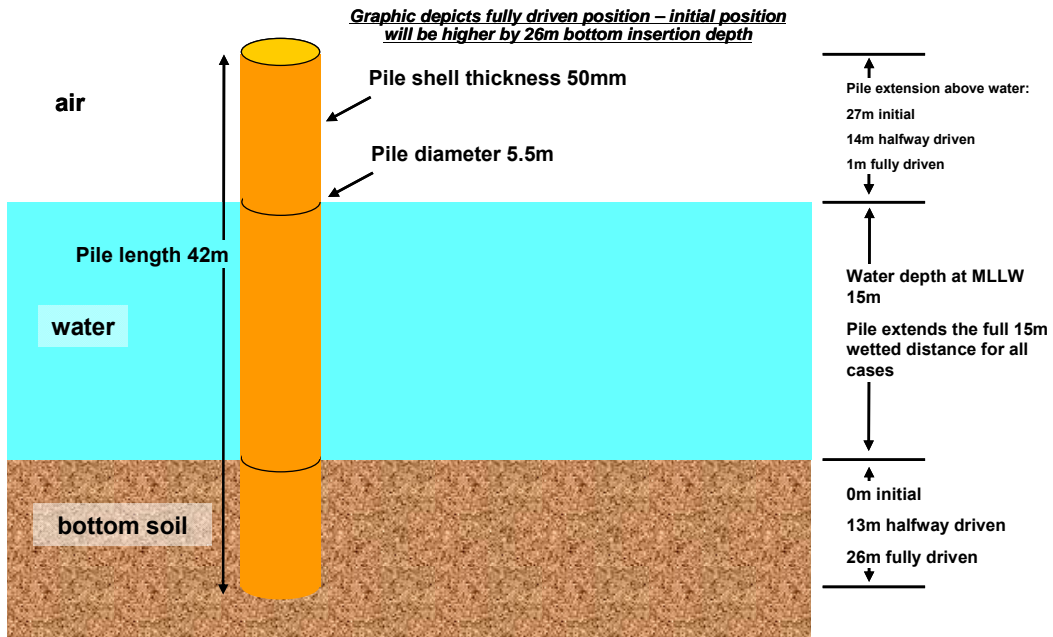


Figure 1: Characteristics of monopile in 15m water depth.

Note: only lower section of full tower assembly is driven into ocean bottom.

Not to scale

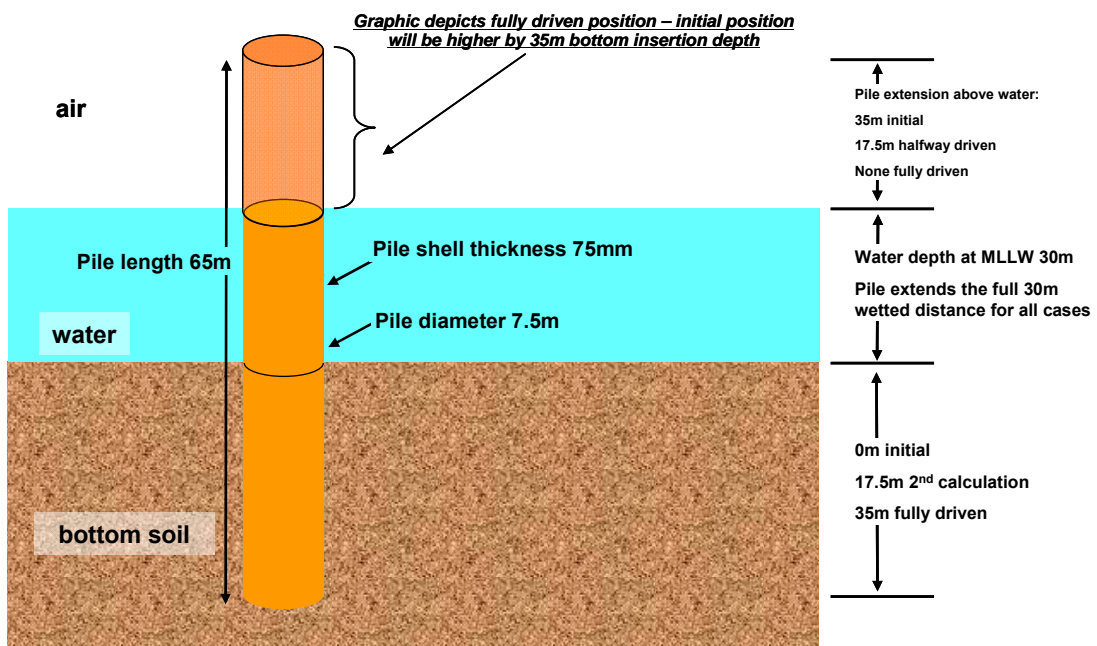


Figure 2: Characteristics of monopile in 30m water depth.

2.3. Baseline Model (No Noise Mitigation)

The baseline model is shown in Figure 3.

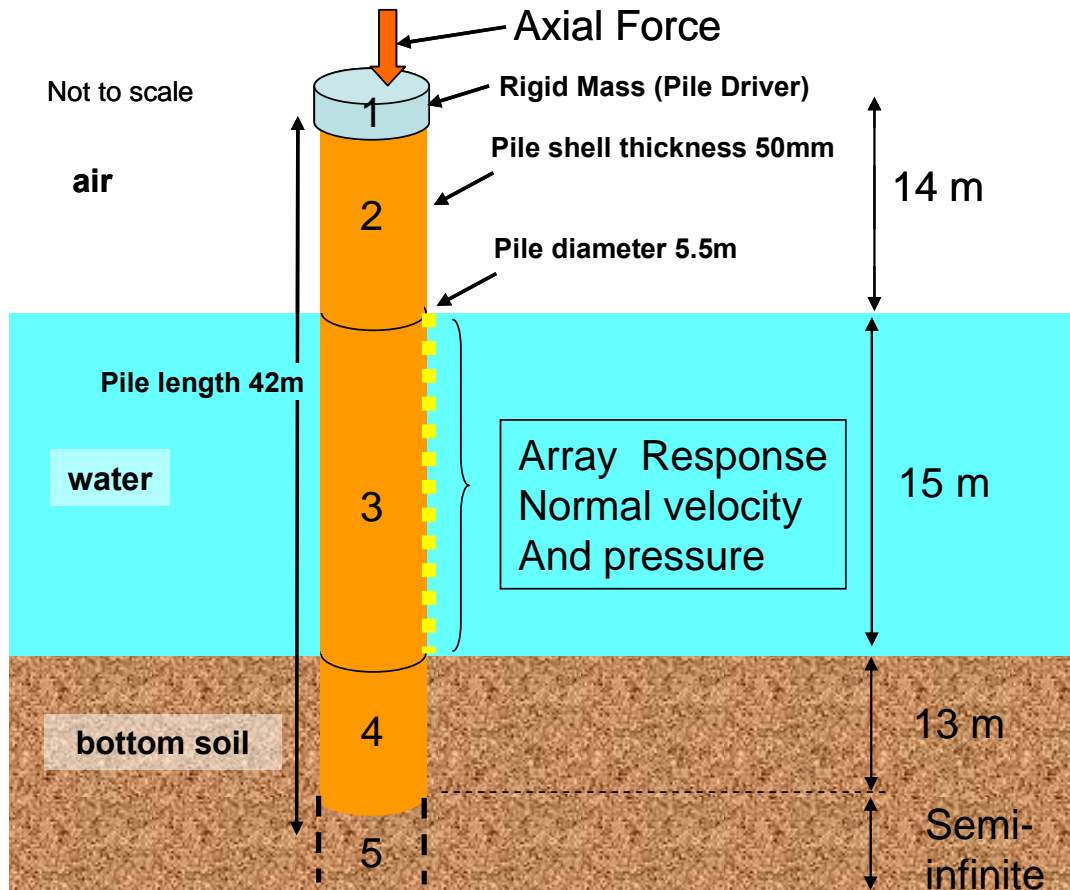


Figure 3: Segments of baseline model.

2.4. Fundamental Concepts of Noise Mitigation

Fundamentally, actions taken to reduce noise can be divided into two sets of options. One is to reduce the source level of the noise producing mechanism. The other is to treat the transmission path that the noise follows from the source to receivers of interest.

In the context of pile driving noise, source reduction requires modification of the blows applied by the driver to the top of the pile. Caps are placed on top of piles during pile driving to prevent mushrooming of the steel due to the repeated blows. Reference [1] discusses a study conducted by the Washington State Department of Transportation on

the effect different caps can have on underwater noise. While caps do reduce noise, they do so by reducing the energy applied to the pile and increasing the rise time of the applied force. This reduces the ability to drive piles into the soil, thus it is not effective to treat pile driving noise by modifying the cap. It is also noteworthy that the greatest noise reductions were found by using wood caps, in place of the synthetic materials normally used. The wooden caps rapidly disintegrated and tended to catch fire, which is a direct result of excessive energy dissipation in the cap.

Treating the transmission path for pile driving noise can be done in two ways. Damping the pile structure will reduce vibration amplitudes resulting from driver blows, resulting in reduced underwater noise. However, the blows generate a wide frequency spectrum of sound, thus tuned dampers (structures designed to damp specific frequencies) would not be effective. Damping material installations which would effectively treat the spectrum of sound generated at the low frequencies observed would need to be extremely massive and complex, and would not be cost effective.

Thus, the promising mechanism for treating the noise transmission path is decoupling, which isolates the pile from the fluid. A basic understanding of decoupling can be gained by comparing a decoupling treatment to a simple spring-mass system. The spring-mass has a resonance, as shown in Figure 4, meaning the mass motion amplitude in response to a given driving force amplitude exhibits a peak at the resonance frequency. At frequencies significantly above resonance, the mass amplitude resulting from a given driving force decreases with increasing frequency. A decoupling treatment is more complex than the simple spring-mass system, however it remains true that decoupling performance is observed at frequencies above the resonance formed by the stiffness of the compliant treatment and the mass loading of the surrounding fluid.

A key insight is that achieving decoupling performance in a target frequency range requires “tuning” the stiffness of the treatment. In particular, treatments with a resonance frequency above the dominant frequency range produced by the driving blows will not be effective. A real world example of this is documented by COWRIE, Reference [2], where a 20mm layer of foam sheeting was applied to a pile. Significant underwater sound reductions were observed at frequencies of 500 Hz and above, but little effectiveness resulted at the critical frequencies extending down to near 100 Hz.

Identification of optimal decoupling treatments requires consideration of different materials in order to provide the required resonant response, while carefully considering the feasibility of installing the treatment around large pilings in the ocean environment. Factors to be considered for treatment design include ability to install the treatment effectively, survivability in the ocean environment, cost, and side effects such as pollution. Decoupling treatment options include air bubbles, close cell foam layers, and containment structures (such as cofferdams or caissons) which allow dewatering the region around the pile. Analysis of these options will consider parameters including thickness, modulus (of rubber or other layers), and bubble fraction (of volume), all of which drive resonance and decoupling performance.

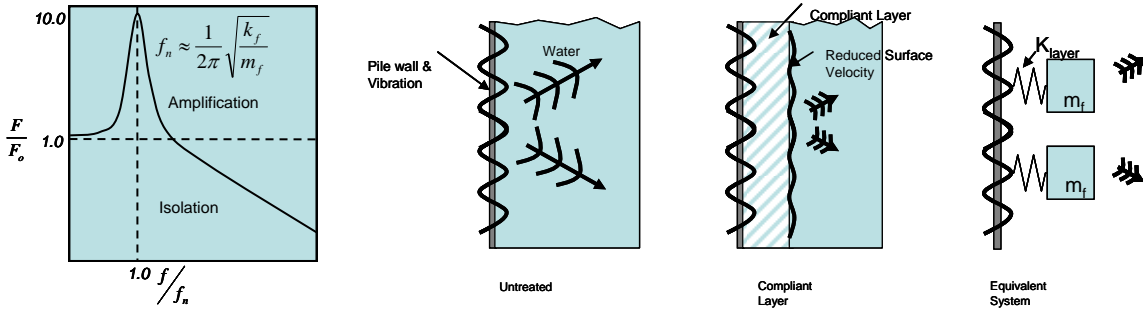


Figure 4: Physics of decoupling treatments.

2.5. Bubble Screen Treated Model

A bubble screen was added at .3 meters from the outside of the pipe wall. The thickness of the bubble screen was 50 mm, which is consistent with treatments of a pile driving noise mitigation study in Washington State, in 2006 Reference [3]. Two void fractions (percent air) of the bubble screen were modeled: 2.5% and 5%. 5% void fraction yields at mid-depth a sound speed given by 75 m/s, which is approximately 5% of the sound speed of the surrounding water column. 2.5% void fraction yields a corresponding sound speed of approximately 100 m/s, a more conservative approach. Formulas for the sound speed of a bubbleswarm are given in Reference [4]. The speed depends upon the void fraction and the depth, and is shown in Figure 5 for a 10 m depth, which is an average value for the pile configuration.

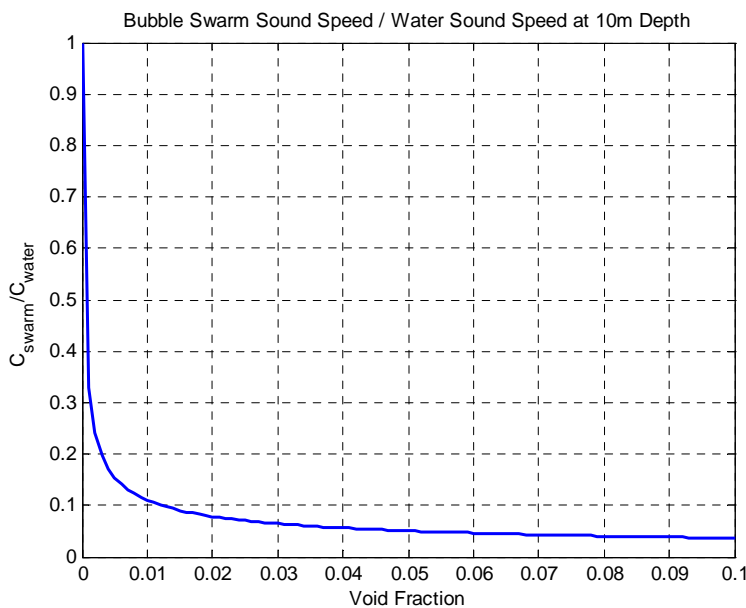


Figure 5: Sound Speed of Bubble Swarm as fraction of Sound Speed of Water, at 10 m

2.6. Closed Cell Foam Treated Model

Closed-cell foam treatments have been shown to be effective in smaller-scale piles (Reference [3]) for mitigating noise due to pile driving activities. To better assess the effect of the foam, three options were modeled: 2 inch, 4 inch, and 8 inch thick layers added to the baseline model. For this study, a foam made of commercially available styrene/butadene rubber (Rubatex R8702) was assumed. Effective material properties for the foam depend upon the void fraction ϕ ; and the shear modulus of the base rubber material μ_H . An approximate formula for the bulk modulus K_{foam} and shear modulus μ_{foam} of foam is given in Reference [5]:

$$K_{foam} = \mu_h \frac{4(1-\phi)}{3\phi}$$
$$\mu_{foam} = \mu_h \frac{(1-\phi)}{(1+2/3\phi)}$$

For this study; the effective shear speed in the Rubatex foam at 50% void fraction was 90 m/s, and the effective compressional speed in the foam was 190 m/s. These relatively slow wave speeds are typical of isolation layers.

2.7. Cofferdam Treated Model

A cofferdam is a highly effective treatment of pile driving noise. In particular, a dewatered cofferdam presents large impedance discontinuities and greatly attenuates sound radiating directly from the pile into the water. We modeled a very massive cofferdam to provide an extreme upper limit on feasible attenuation of this path. Figure 6 and Figure 7 present the cofferdam details used for our model.

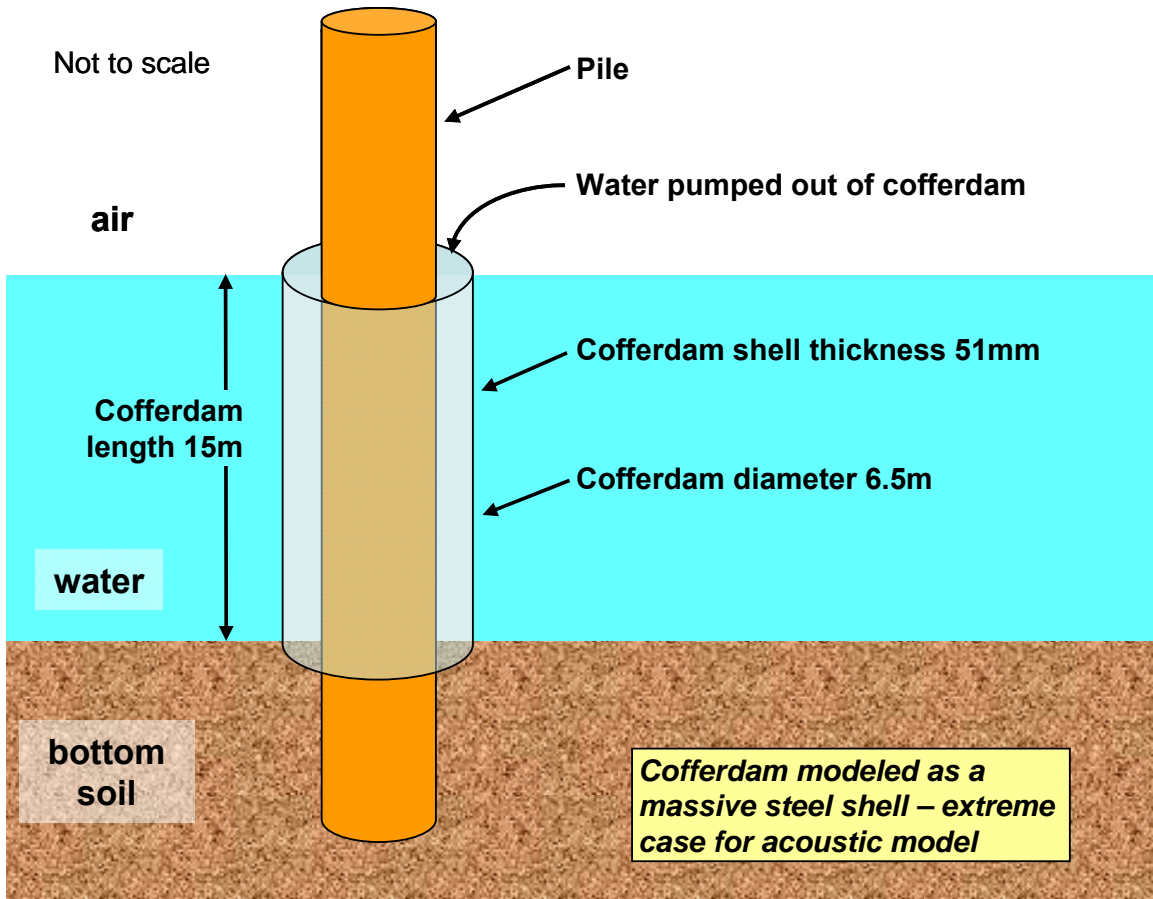


Figure 6: Cofferdam details for 15m deep ocean.

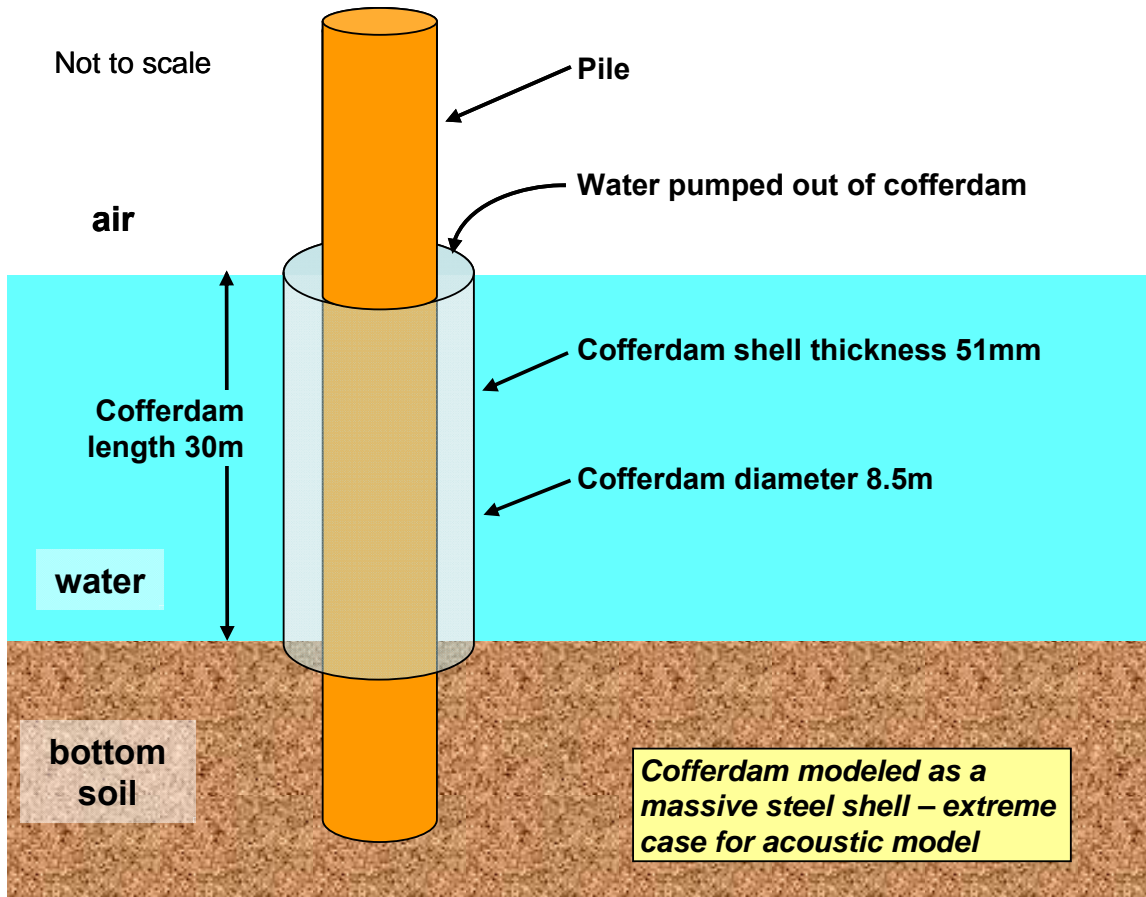


Figure 7: Cofferdam details for 30m deep ocean.

Additionally, we ran sets of cases that examined the effects of the material inside the pile with a cofferdam in place. As a default, the pile would be filled with water, which would enter as the pile was lowered to the bottom (and which would rapidly fill in through the open pile bottom if it was initially evacuated, unless it was continuously pumped out). Two additional alternatives were analyzed: (1) pile filled with air; and (2) pile filled with mud. As discussed below, the seismic path becomes a significant or controlling path with a cofferdam installed, and thus imposes a limit on cofferdam effectiveness. The intent of the mud filled case was to determine whether the mud would apply damping to the structure, resulting in a reduction of energy transmitted to the bottom, thus reducing the seismic path and improving the overall performance with a cofferdam in place. Similarly, the air filled case examines whether dewatering the inside of the pile reduces sound transmission into the bottom.

2.8. Virtual Source Technique

The multi-layer waveguide (DTL) method predicted the pressure and particle velocity in the water, air, and silt due to the vibration of the pile, in the vicinity of the pile. Like most

full finite element models, the exterior environment (air/water/silt) is terminated with a non-reflecting boundary condition. In order to propagate the field far away from the pile, for environmental assessment, it is necessary to use a propagation model, such as OASES (MIT/SACLANT). Like all ocean propagation models, OASES does not include the elastic pile or any mitigation treatments. As a result, it is necessary to compute effective or virtual sources that would produce the same field in the nearfield of the pipe, so that pressure and radiated power can be computed. The basic idea of the technique is that virtual source amplitudes (Figure 8 - red/yellow circles) are found which match the pressure and the radial derivative of the pressure (normal to the surface of the pile). These pressures are computed from the transmission line model, which includes the pile, the drive, and any mitigation treatments. The points to match pressure are located approximately 4 meters outside the pile radius, and are illustrated in green in Figure 8. Because pressure is matched along 2 arrays, a finite difference scheme is used to compute pressure and its normal derivative with respect to the surface:

$$p(R_s); \frac{d}{dn_s} p(R_s)$$

The normal acoustic particle velocity v_r is related to the pressure normal derivative by:

$$\frac{d}{dn_s} p(R_s) = \rho i \omega v_r$$

When the pressure and radial component of the particle velocity are matched, it follows that the radial component of time-averaged intensity will be matched:

$$I_r = 1/2 \text{re}(p^* v_r)$$

The match of intensity is critical to ensure that power flow through the layers is maintained, and acoustic mitigation techniques can be accurately assessed.

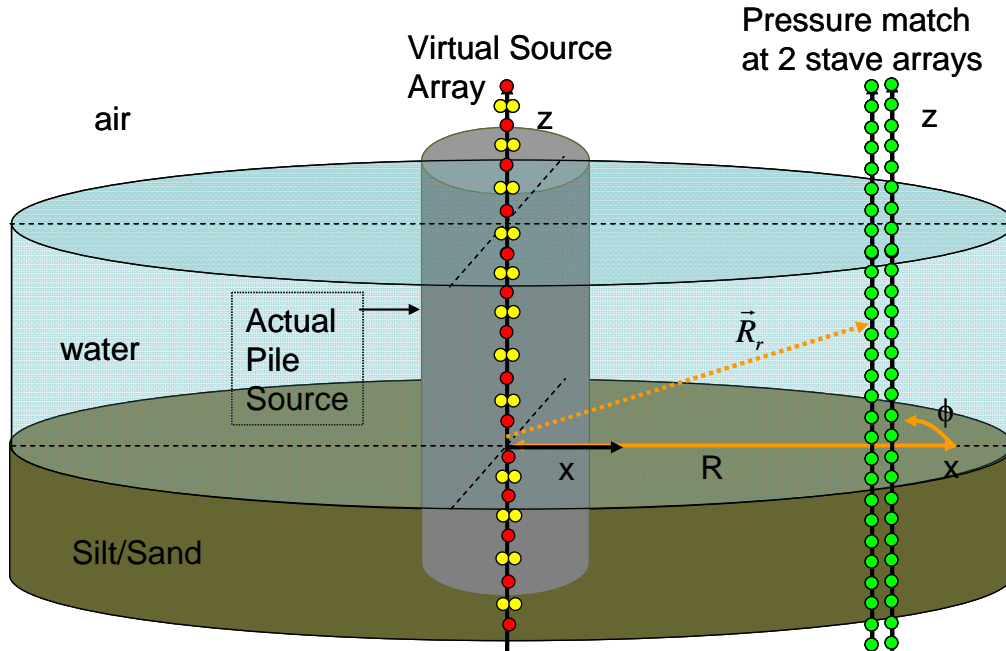


Figure 8: Virtual Source Technique (Waveguide to OASES coupling)

Results for the virtual source technique are shown for the bubble screen baseline case at 500 Hz in Figure 9. Because transfer functions are of interest, the results are normalized to a 1 N axial load at the top of the pile. The intensity results show that because the bubble screen is present, most energy travels through the soil (below the red line at $z=15$).

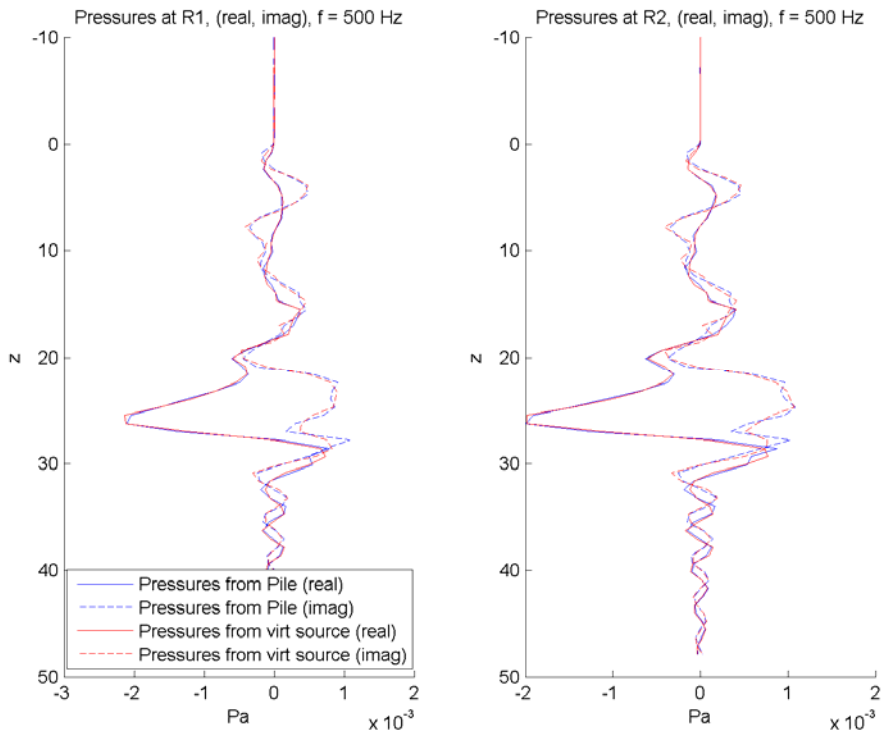
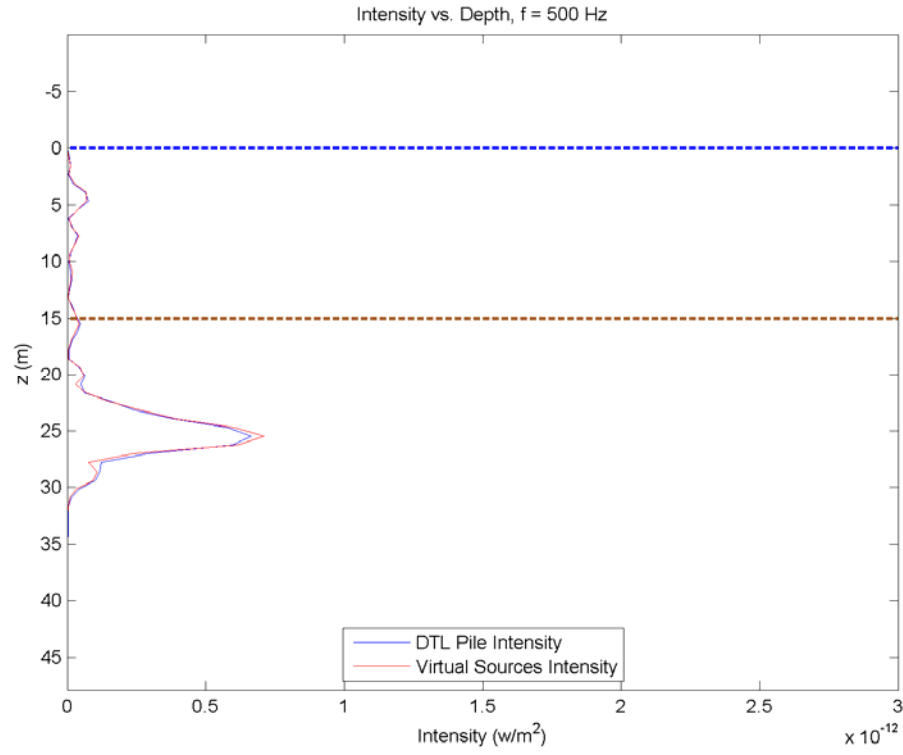


Figure 9: Match of physical pile model to virtual source technique for the bubble screen baseline case. $Z=0$ is the air/water interface. $Z=15$ is the water/soil interface. Intensity match shown is shown in the upper plot; pressure at the two receiver stave arrays is shown in the lower plot.

Experiments with the virtual source technique have led to a set of algorithm guidelines, which are described below:

1) Spacing of Virtual Sources.

The virtual sources have a spacing of $\lambda/2$, where λ is the wavelength in water. Although closer spacing allowed for a more accurate "matching" of the pressure field, closer spacing also caused the algorithm that finds the virtual source amplitudes to become unstable (i.e., the condition number of the inversion matrix blows up). Spacing of $\lambda/2$ proved to be a good compromise between accurately matching the field, and keeping the problem stable.

2) Location of the virtual sources.

The field was "matched" on a cylindrical surface extending 20 meters beyond the top and bottom of the pile, at a radius of about 1 meter larger the pile's radius. The virtual sources were all at a radius of zero, and were no closer than $2*\lambda_{\text{water}}$ from the top and bottom of the cylindrical matching surface. The justification for this constraint was that it is impossible for the pile to radiate energy from locations where the pile does not exist. Thus any virtual sources outside this region would be unphysical artifacts of the (imperfect) modeling techniques.

3) Algorithm for finding the virtual source amplitudes.

Theoretically, the pressure and the radial velocity must be matched on the cylindrical surface. Because the radial velocity is proportional to the radial derivative of the pressure, one can match the pressure on two cylindrical surfaces with closely spaced radii (relative to the wavelength) instead of matching the pressure and radial velocity on one surface. The pressure field is "matched" on two cylindrical surfaces extending 20 meters beyond the top and bottom of the pile. The first cylinder has a radius of about 4 meters larger than the pile's radius, the second has a radius of $\lambda/4$ larger than the first.

Because the problem is axially symmetric, the pressures only need to be matched along a vertical line, not on the entire cylindrical surface. Furthermore, because the problem is being solved numerically, a discrete set of points where the pressure was to be matched were placed along that line (on each cylinder). The points were spaced at approximately $\lambda/2$. Although finer spacing would theoretically improve the results, finer spacing made the least-squares algorithm unstable, and we don't expect the pressure to change on scales much finer than $\lambda/2$.

2.9. Effect of Downward-Sloping Environment on Sound Levels

A side study was conducted to investigate the effect a sloping bottom would have on sound levels. The analyses presented in this report have been based on the assumption that the seafloor is flat (range-independent). This range-independent assumption is common in ocean-acoustic research because it is reasonably accurate over most common environmental conditions and it is efficient to model computationally. For the environments considered in this report, the assumption of a flat seafloor may not be accurate. For example, water depths at the Cape Wind site vary from less than 10 ft on Horseshoe Shoal to over 50 ft in the surrounding Nantucket Sound. This raised the question of what, if any, effect this downslope (from a pile on the shoal to the sound) environment will have on the acoustic propagation and the resulting sound levels.

Downslope propagation has been extensively discussed in the literature (for a review see Carey and Wagstaff, 1986). It has been found that, when sound propagates down a slope, it suffers less transmission loss than it would in an equivalent flat-seafloor environment. In other words the received sound levels will be somewhat louder in a downslope environment. This phenomenon has been termed ‘downslope enhancement’ (DSE). Several experiments have been described in the literature describing the measured DSE under various environmental conditions. The experiment that most nearly replicates the conditions at Cape Wind (i.e.: relatively shallow water) was done by Carey, Gereben and Brunson (1987). They measured an increase in sound levels (above what would be expected for a flat bottom) of between 2 and 6 dB. Other published experiments give similar DSEs.

This means that the actual sound levels at Cape Wind are likely to be a few dB higher than would be predicted using a range-independent acoustic propagation model. Caution should be exercised; however, and one should not expect exactly the same DSE at Cape Wind as was measured in previous experiments since the precise geometries and environments differ.

Fortunately, since the purpose of the current research is to evaluate noise paths from the pile to the water and comparing various noise mitigation measures, the DSE is not a factor. This is because the long range propagation due to the environment is independent of sound mitigation effort near the pile. In other words, the DSE for a bare pile is the same as the DSE for a pile with a noise mitigation treatment. So if our range-independent model predicts a certain sound reduction due to a given mitigation measure, that same sound reduction will occur in a range-dependent environment. Thus, the flat bottom assumption used for the model described herein provides accurate results that are applicable to sloping ocean bottoms.

3. Summary of Results

In summary, Phase 1 was very successful. The objectives of quantifying acoustic transmission paths, and identifying and ranking noise mitigation concepts, were successfully accomplished. The key to this success was development and application of a physics-based model which enables detailed assessment of the acoustic characteristics of pile hammering, structural response, propagation through water, ground, and air, and treatment performance. The Phase 1 results provide a strong basis for proceeding to the design development and prototyping work envisioned in Phases 2 and 3 of this program. A summary of accomplishments follows.

To enable a detailed evaluation of pile parameters and treatment options, a very large set of configurations were analyzed. These configurations included:

1. 15m and 30m water depth (with the corresponding effect on pile dimensions).
2. Treatment options including: no treatment; several options of compliant layer on the pile; several options of bubble screen, and a dewatered cofferdam modeled as a thick and very rigid structure considered to be an extreme case of the most effective possible treatment.
3. Underwater sound locations near the bottom, in the middle of the water column, near the surface, and an average across depths, all calculated as a function of range.
4. Results at frequencies of 100 to 1000 Hz, which evaluation of existing pile driving noise data indicate is the dominant frequency range. Many examples of this are provided by the California Department of Transportation (CALTRANS) Reference [6].

Additionally, the extent to which the pile is driven has a potentially large impact on the overall noise transmitted into the water, due to the different size of the radiating surfaces in air and in the ocean bottom, and due to the impact on the overall pile boundary conditions. For this reason, the model was run for three pile driven extents: first contact with the ocean bottom, halfway driven, and fully driven.

As discussed above, the objective of this modeling effort is to establish the relative importance of the three primary transmission paths and to assess the potential effectiveness of several mitigation options. Thus, the results are provided in terms of transfer function, i.e. resultant underwater noise normalized to a force input magnitude of 1 pound, directed axially at the top of the pile. These transfer functions provide a common basis for comparing analysis cases that are valid for any input force magnitude.

Due to the complexity of the analysis and results, and the many parameters affecting the results, five different visualizations were developed. These consist of:

1. Transfer function as a function of depth and range, at frequencies of 100 Hz, 200 Hz, 400 Hz, 800 Hz, and 1000 Hz. These are presented in the form of color-scaled plots, with transfer function magnitude expressed via color as a function of

- depth and range on the axes. These provide a high fidelity visualization of the complexity of the resultant underwater noise fields.
2. Transfer function at a specific depth and range, as a function of frequency, calculated at a range of 30m from the pile. These are presented in the form of line plots. As noted in the color-scaled plots of transfer function versus range and depth, the sound field varies considerably as a function of position, so the results are averaged over a 1m cube. These results are representative of measurements conducted with a hydrophone during actual pile driving operations.
 3. Depth averaged transfer function as a function of frequency, calculated at ranges of 10m, 100m, and 300m from the pile. Well established energy flux methods for averaging acoustic intensity across depth were used to calculate these averages. These provide a comparison of the effect of the different treatment options.
 4. Depth averaged transfer function as a function of range from the pile, calculated at frequencies of 100 Hz, 200 Hz, 400 Hz, and 800 Hz. These provide an alternative comparison of the effects of the different treatment options.
 5. Depth averaged transfer function as a function of frequency for the overall result (summation of all three paths) compared to the individual path contributions, as a function of frequency. These are also calculated at ranges of 10m, 100m, and 300m from the pile. These enable an assessment of the relative contributions of each sound path.

This report section provides representative result plots and describes the findings. The following sections provide detailed results for the cases analyzed. Table 2 presents the matrix of test cases analyzed.

Table 2 – Matrix of analysis cases.

Ocean Depth (m)	Pile Diameter (m)	Pile Insertion	Treatment
15	5	None: 0 m	Untreated
			Bubble Screen (5% volume fraction)
			Closed cell rubber foam (4 inch thick)
		Half: 13 m	Untreated
			Bubble Screen (2.5% volume fraction)
			Bubble Screen (5% volume fraction)
			Closed cell rubber foam (2 inch thick)
			Closed cell rubber foam (4 inch thick)
			Closed cell rubber foam (8 inch thick)
			Dewatered cofferdam (Type 1, air inside pile)
			Dewatered cofferdam (Type 2, water inside pile)
			Dewatered cofferdam (Type 3, mud inside pile)
		Full: 26 m	Untreated
			Bubble Screen (5% volume fraction)
			Closed cell rubber foam (4 inch thick)
30	7.5	None: 0 m	Untreated
		Half: 17.5 m	Untreated
			Bubble Screen (5% volume fraction)
			Closed cell rubber foam (4 inch thick)
			Dewatered cofferdam (Type 2, water inside pile)
		Full: 35 m	Untreated

The results clearly support evaluation of the primary transmission paths and mitigation concept options.

3.1. Transmission Paths

Findings regarding the transmission paths can be summarized as follows:

1. The structureborne radiation (water) path dominates underwater noise for nearly all cases. Figure 10 provides a representative example.
2. The seismic propagation path is not a significant contributor to underwater noise for the untreated case, where the seismic contribution is 10 to 30 dB below the combination of all paths. The seismic contribution is the limiting factor on the overall effectiveness of treating the structureborne radiation path. With bubble screen or compliant layer treatments, the seismic path becomes a contributing or

occasionally controlling path at a few frequencies. With a dewatered cofferdam installed (the most effective treatment) the seismic path is the controlling path at most frequencies. Figure 10, Figure 11, and Figure 12 present representative examples of this behavior.

3. The airborne transmission path is not a significant contributor to underwater sound in any case. Even with the cofferdam, the airborne path contribution is 50 dB or more below the combination of all paths. Figure 10, Figure 11, and Figure 12 present representative examples of this behavior.

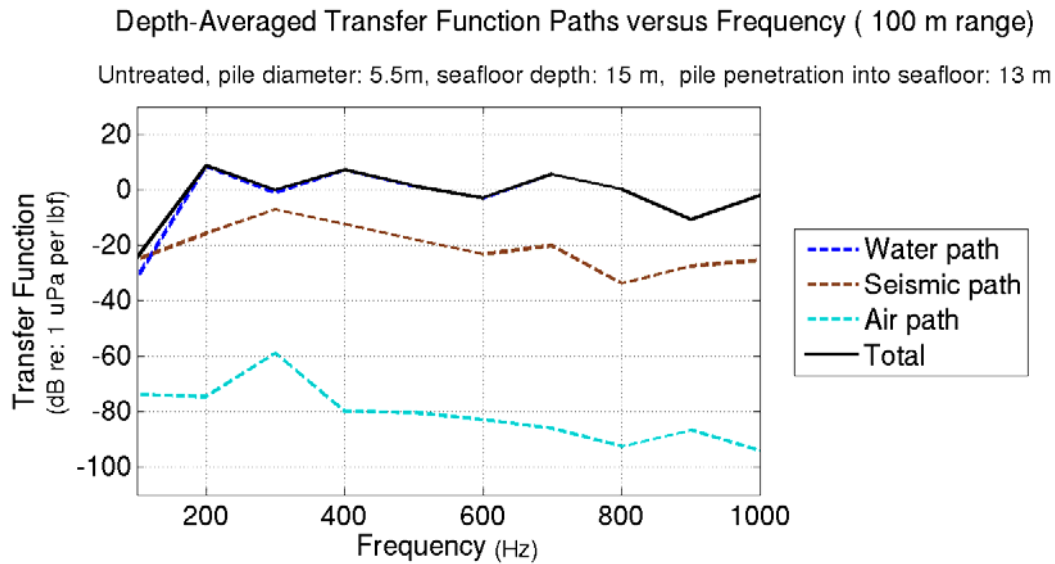


Figure 10: Representative transmission path components for untreated pile.

Depth-Averaged Transfer Function Paths versus Frequency (100 m range)

Rubatex (4 inch), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m

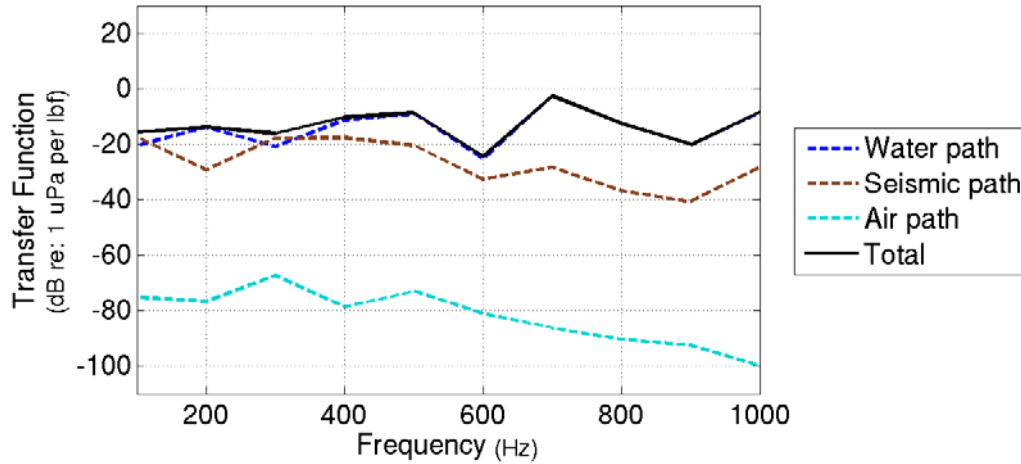


Figure 11: Representative transmission path components for pile treated with compliant surface treatment (bubble screen similar).

Depth-Averaged Transfer Function Paths versus Frequency (100 m range)

Cofferdam (type 2), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m

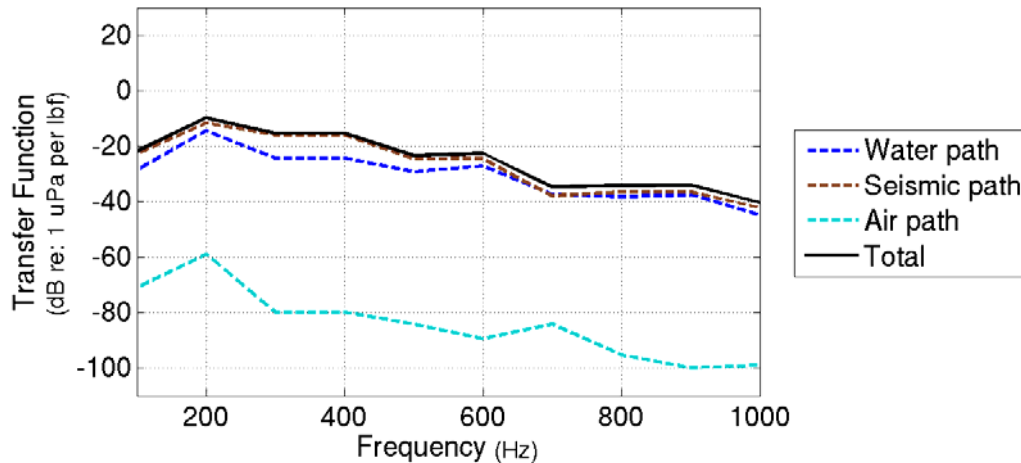


Figure 12: Representative transmission path components for pile treated with cofferdam.

Figure 13 through Figure 16 provide representative cases of the transfer function as a function of depth and range from the pile for various treatment options, further illustrating the relative path contributions. These data are at 800 Hz, and illustrate the trends over the frequency band modeled. In Figure 13, which shows the untreated pile, the structureborne radiation (water) path contribution is virtually identical to the overall transfer function, showing that the water path is completely dominant. The seismic path is well below the water path, and the airborne path is much lower still. Figure 14

presents the pile with 4 inch Rubatex, and shows that the water path is still dominant, although it has been attenuated enough that the seismic path is closer to the combined result. The airborne path contribution is still far below the other paths. Figure 15, which shows the bubble screen case with 5% bubble fraction, indicates similar relative contributions as the 4 inch Rubatex – again the water path is dominant but has been attenuated so the seismic path is closer. Figure 16 shows the pile with a dewatered cofferdam. In this case, the water path contribution has been attenuated to the point that it is very similar to the seismic path. Further reduction of the water path would have little effect on the overall levels, due to the “floor” resulting from the seismic path contribution. Even in this case, the airborne path is far below the others, and is not a significant contributor.

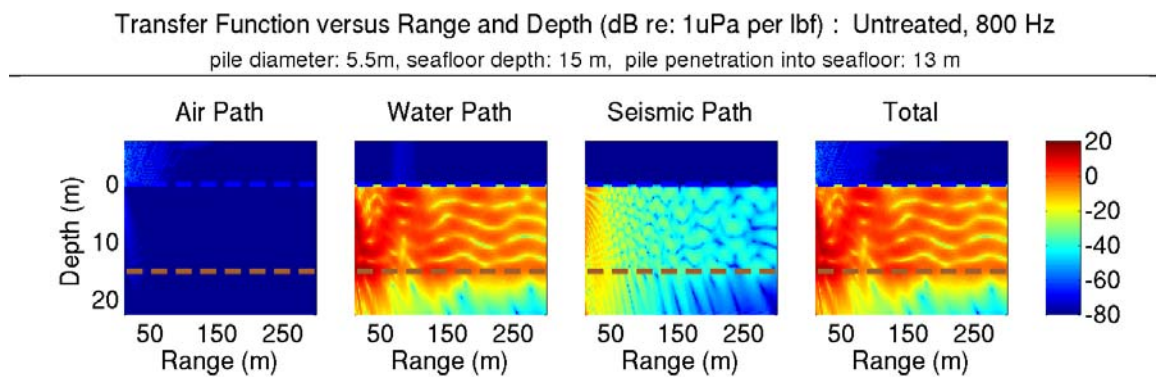


Figure 13: Transfer function as a function of depth and range, untreated.

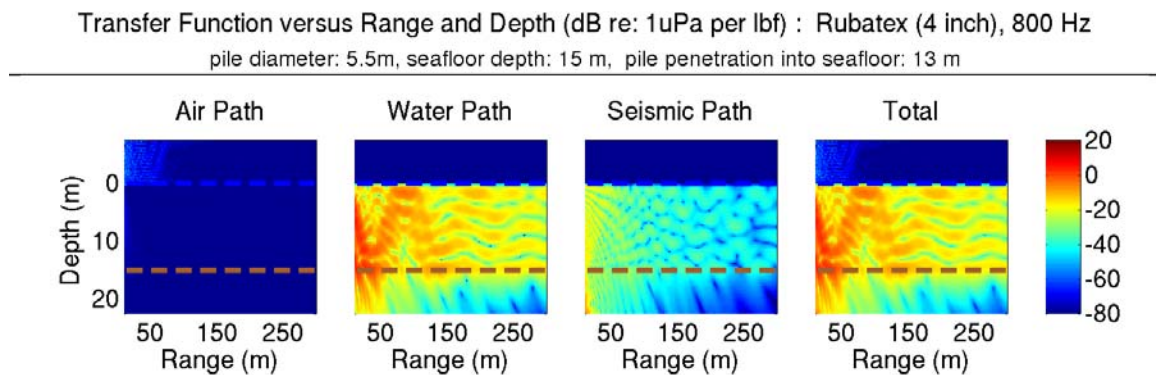


Figure 14: Transfer function as a function of depth and range, 4 inch Rubatex.

Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Bubble screen (5 %), 800 Hz
 pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m

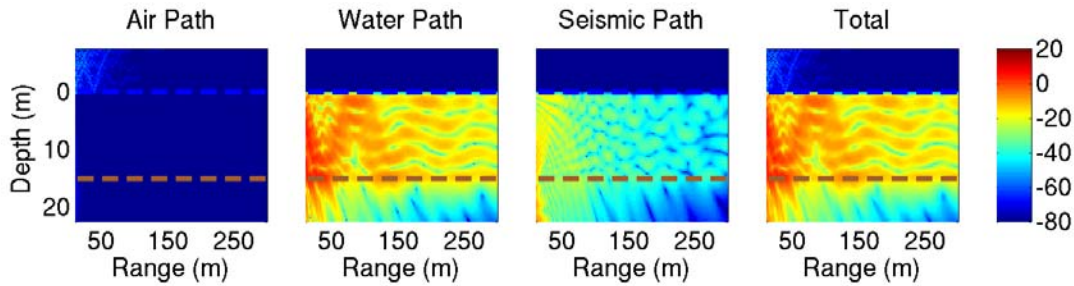


Figure 15: Transfer function as a function of depth and range, 5% fraction bubble screen.

Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Cofferdam (type 2), 800 Hz
 pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m

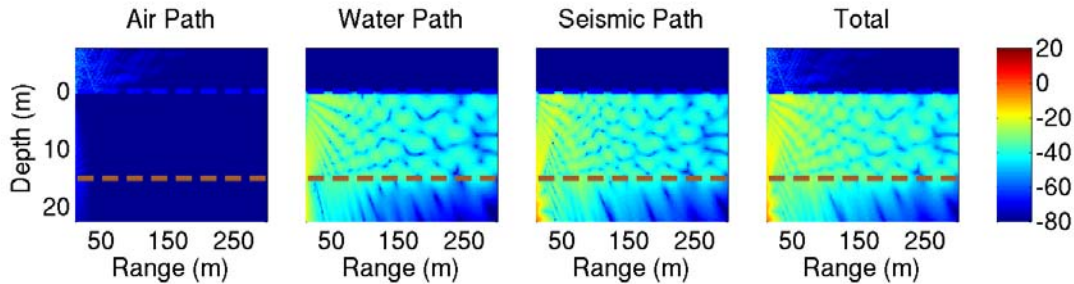


Figure 16: Transfer function as a function of depth and range, dewatered cofferdam with water inside pile.

3.2. Sound Mitigation Options

Findings regarding the underwater sound mitigation concept options can be summarized as follows. Note that these predictions are condensed from a large body of information. Specific actual installations will vary in performance, but these predictions are considered to be an effective quantification of relative performance that can be used to support evaluation of potential pile installations and design concept development.

1. A bubble screen is predicted to reduce noise levels by approximately 10 dB. Variation of air volume fraction in the range of 2.5% to 5% does not significantly affect this result.
2. A compliant surface treatment is predicted to reduce noise levels by approximately 10 dB. Varying thickness of the treatment in the range of 2 inches to 8 inches does not significantly affect this result.
3. A dewatered cofferdam is predicted to reduce noise levels by approximately 20 dB. This is considered to be the upper bound on possible noise mitigation

treatment performance. With a dewatered cofferdam, the inside of the pile will fill with water unless action is taken to keep it out. Excursions of the model with air inside the pile (water pumped out), and with the pile filled with mud (in an effort to damp sound transmitted to the bottom) show no significant impact on performance.

Figure 17 is a set of representative results that compares the performance of the key mitigation concepts modeled.

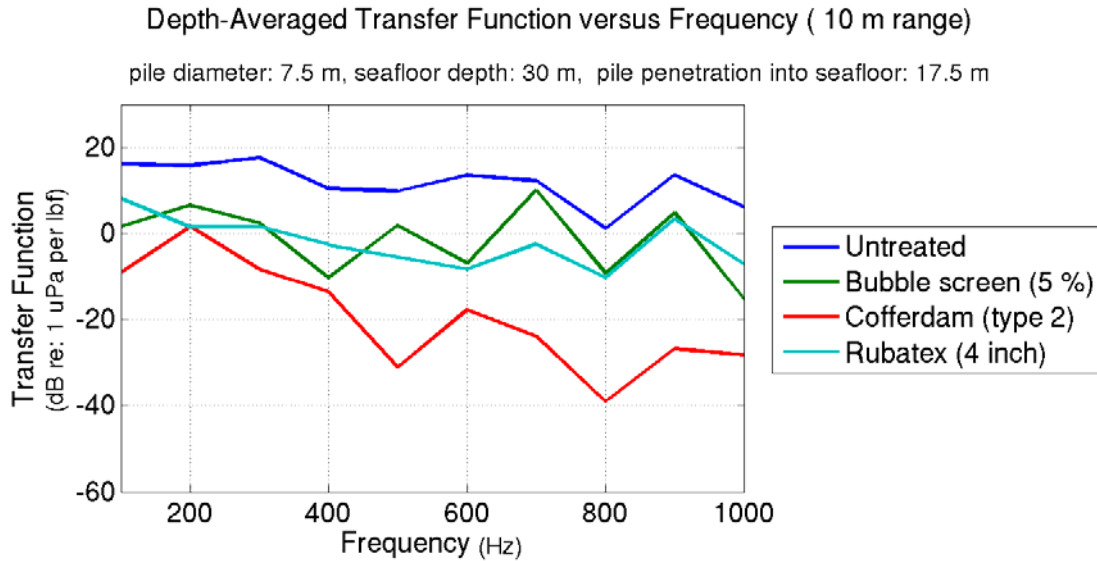


Figure 17: Representative comparison of mitigation option performance.

4. Conclusions

The results clearly support evaluation of the primary transmission paths and mitigation concept options. Findings regarding the transmission paths can be summarized as follows:

1. The structureborne radiation path dominates underwater noise for nearly all cases.
2. The seismic propagation path is not a significant contributor to underwater noise for the untreated case, where the seismic contribution is 10 to 30 dB below the combination of all paths. The seismic contribution is the limiting factor on the overall effectiveness of treating the structureborne radiation path. With bubble screen or compliant layer treatments, the seismic path becomes a contributing or occasionally controlling path at a few frequencies. With a dewatered cofferdam installed (the most effective treatment) the seismic path is the controlling path at most frequencies.

3. The airborne transmission path is not a significant contributor to underwater sound in any case. Even with the cofferdam, the airborne path contribution is 50 dB or more below the combination of all paths.

Findings regarding the underwater sound mitigation concept options can be summarized as follows. Note that these predictions are condensed from a large body of information. Specific actual installations will vary in performance, but these predictions are considered to be an effective quantification of relative performance that can be used to support evaluation of potential pile installations and design concept development.

1. A bubble screen is predicted to reduce noise levels by approximately 10 dB. Variations in air volume fraction in the range of 2.5% to 5% does not significantly affect this result.
2. A compliant surface treatment is predicted to reduce noise levels by approximately 10 dB. Varying thickness of the treatment in the range of 2 inches to 8 inches does not significantly affect this result.
3. A massive dewatered cofferdam is predicted to reduce noise levels by approximately 20 dB. This is considered to be the upper bound on possible noise mitigation treatment performance. Model excursions showed no significant difference between cases with the inside of the pile filled with water, air, or mud.

These modeling results provide a basis for evaluating sound mitigation options with respect to specific requirements, such as frequencies and sound levels which have adverse impacts on specific species of marine life found at specific locations a wind farm is to be installed. These specific requirements will yield mitigation performance metrics which will be used for optimization analysis to identify the most feasible and cost effective design. This optimization analysis is a key element of the design development and prototype implementation and evaluation work proposed for Phases 2 and 3.

Additionally, a side study was conducted which indicated that a non-level bottom would not significantly affect these findings.

5. Upcoming Work

This report is our final report for Phase 1 of the pile driving noise mitigation project. The work presented herein fully encompasses the objectives of Phase 1, in particular comparing the importance of different transmission paths, and assessment of mitigation options. We have also conducted a final presentation for MMS, at which these results were discussed. This final report is an update of the draft provided earlier, and has been revised to address MMS comments. The Phase 1 results provide a strong basis for continued work to design and prototype noise mitigation for pile driving noise, as proposed in Phases 2 and 3 of this project.

References:

- [1] Laughlin, J., “Underwater Sound Levels Associated With Pile Driving at the Cape Disappointment Boat Launch Facility, Wave Barrier Project”, Washington State Department of Transportation Office of Air Quality and Noise, March, 2006.
- [2] Nehls, G., Betke, K., Eckelmann, S. & Ros. M., “Assessment and Costs of Potential Engineering Solutions for the Mitigation of the Impacts of Underwater Noise Arising from the Construction of Offshore Windfarms”, BioConsult SH report COWRIE ENG-01-2007, on behalf of COWRIE Ltd., September, 2007.
- [3] MacGillivray, A, “Underwater Acoustic Measurements from Washington State Ferries 2006 Mukilteo Ferry Terminal Test Pile Project”, prepared for the Washington State Ferries & Washington State Department of Transportation, March 6, 2007.
- [4] Junger, M. and Cole, J, “Bubble Swarm Acoustics”, J. Acoust. Soc.Am. 68(1), July 1980, p. 241-247.
- [5] Deigan, Richard J. “Modeling And Experimental Investigations Of The Shock Response Of Viscoelastic Foams” Ph.D Dissertation, University of Maryland, 2007.
- [6] ICF Jones & Stokes and Illingworth and Rodkin, Inc, “Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish”, prepared for the California Department of Transportation, February 2009.

Appendices

A. Transfer Function as a Function of Depth and Range

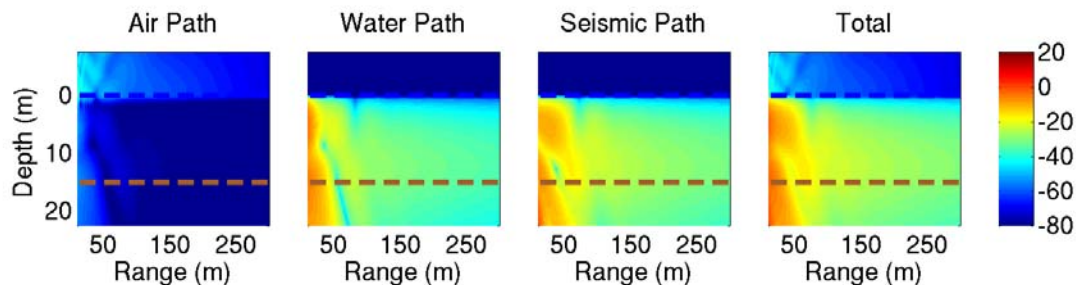
The following figures provide transfer function as a function of depth and range, at frequencies of 100 Hz, 200 Hz, 400 Hz, 800 Hz, and 1000 Hz. As discussed earlier, these provide a high fidelity visualization of the complexity of the underwater noise fields resulting from pile driving. Each plot shows the total calculated transfer function, and the individual contributions of the airborne, structureborne radiation (water), and seismic paths.

These illustrate that the sound varies substantially with position, with higher and lower level regions resulting from the modal response of the system. They clearly illustrate that the airborne path is not a significant contributor, and that the water path is dominant except with a cofferdam installed. Note the dashed line indicates the location of the ocean bottom. As indicated in the legend scale, the colors correspond to the transfer function at each point as a function of depth and range. These plots are all for the pile driven halfway into the ocean floor.

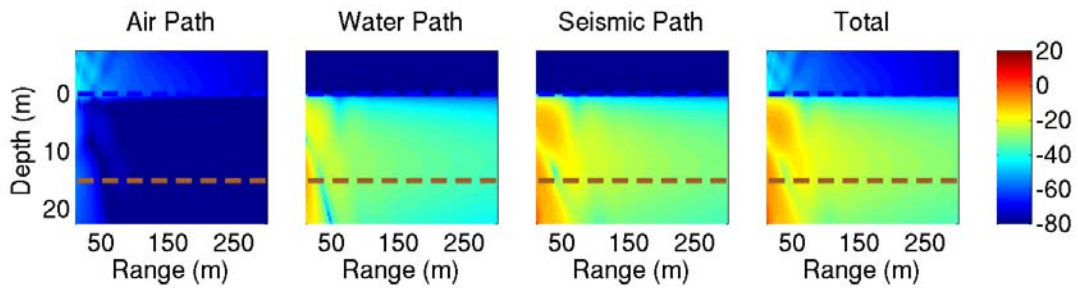
15 Meter Ocean Depth

100 Hz:

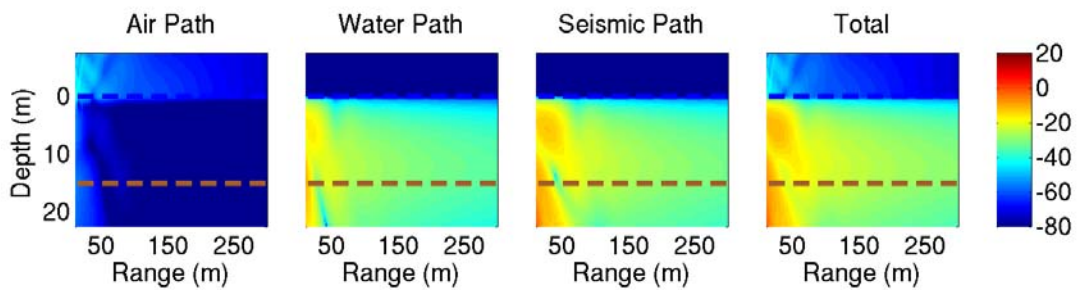
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Untreated, 100 Hz
pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Bubble screen (2.5 %), 100 Hz
 pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m

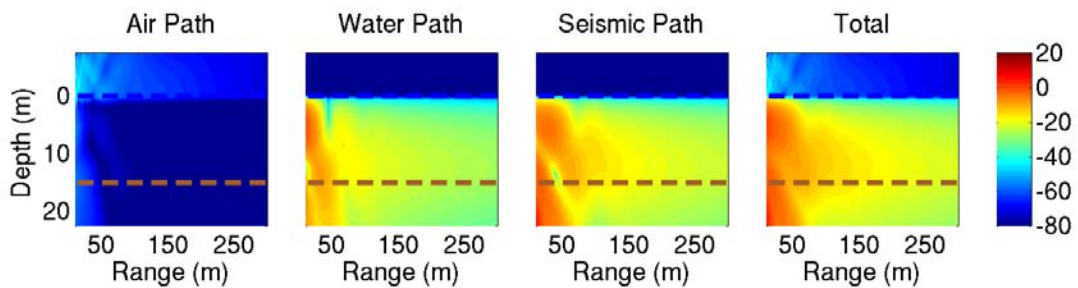


Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Bubble screen (5 %), 100 Hz
 pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



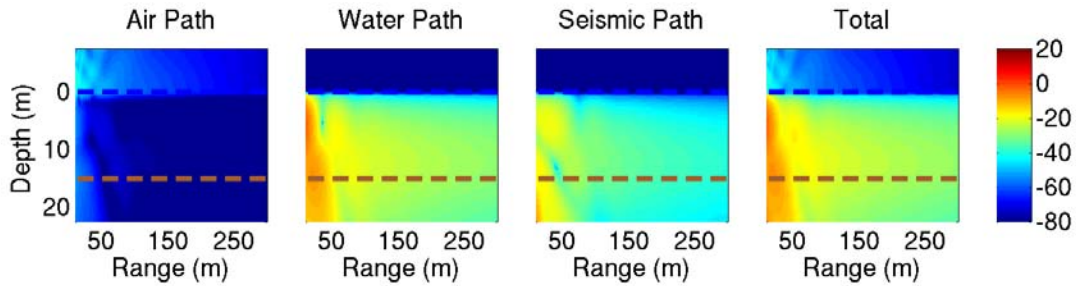
Note: 15m bottom model computations did not converge properly for 2 inch Rubatex at 100 Hz, so this plot is omitted.

Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Rubatex (4 inch), 100 Hz
 pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



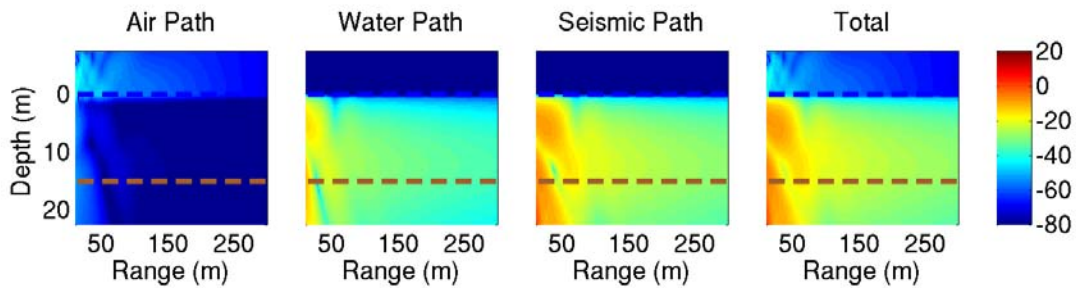
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Rubatex (8 inch), 100 Hz

pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



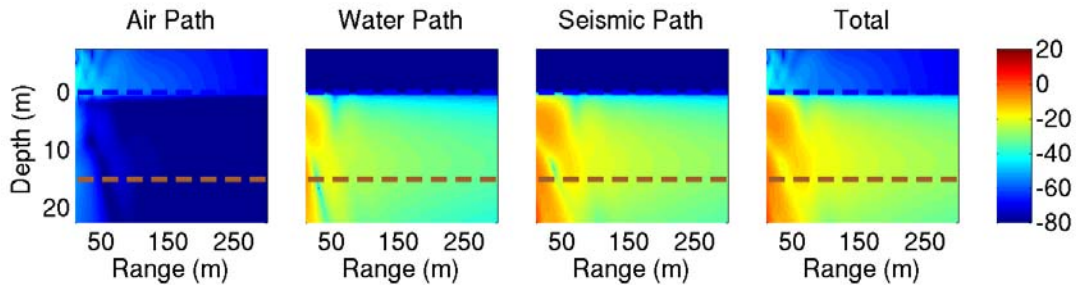
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Cofferdam (type 1), 100 Hz

pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



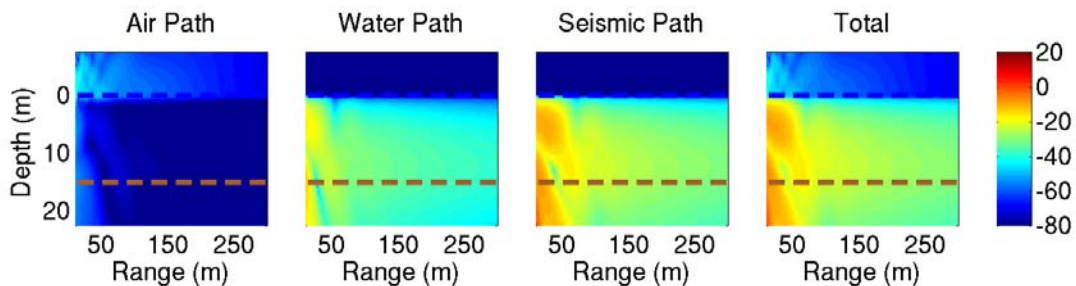
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Cofferdam (type 2), 100 Hz

pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Cofferdam (type 3), 100 Hz

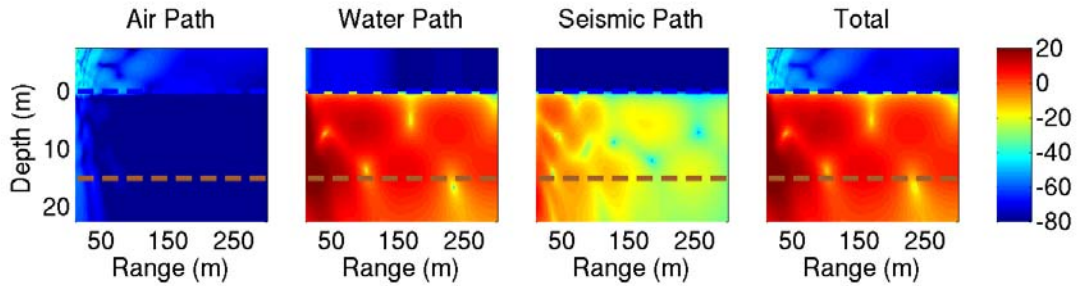
pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



200 Hz:

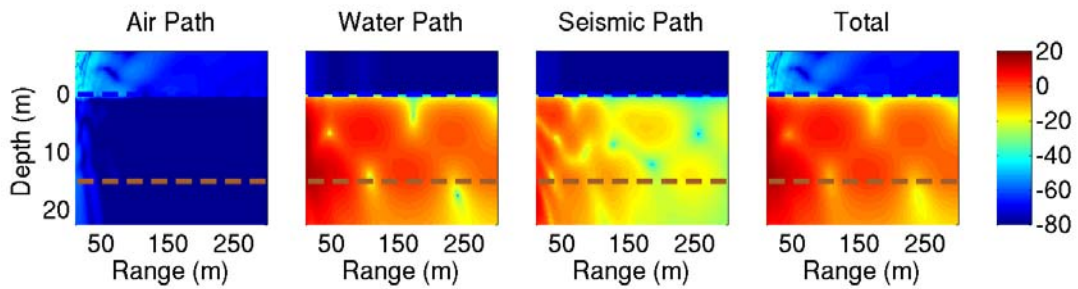
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Untreated, 200 Hz

pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



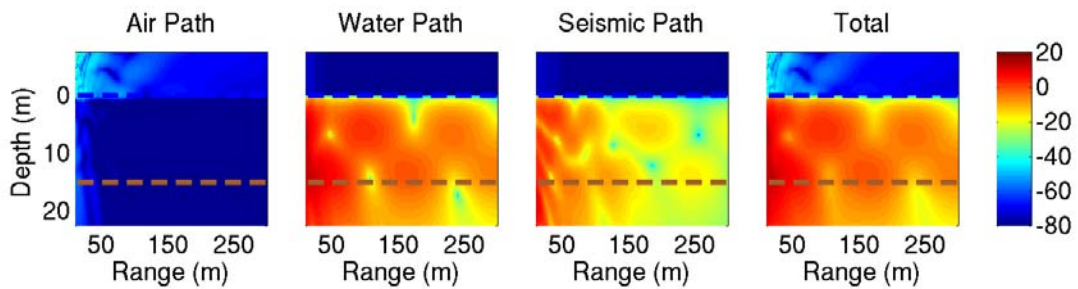
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Bubble screen (2.5 %), 200 Hz

pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



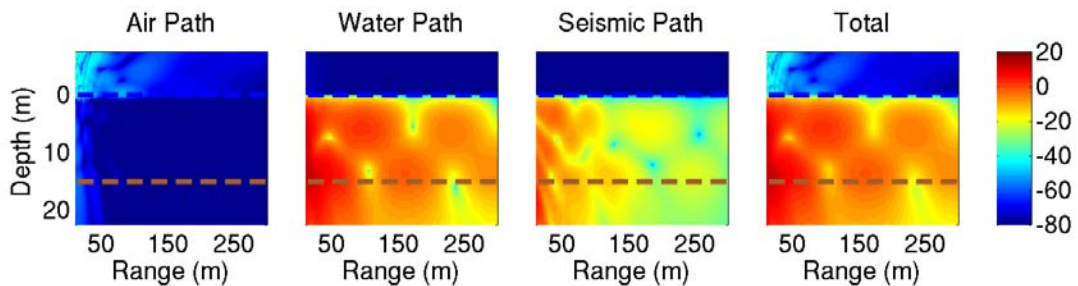
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Bubble screen (5 %), 200 Hz

pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



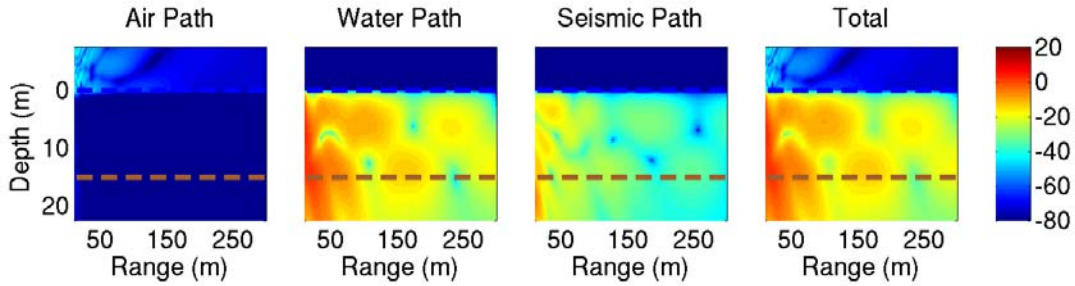
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Rubatex (2 inch), 200 Hz

pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



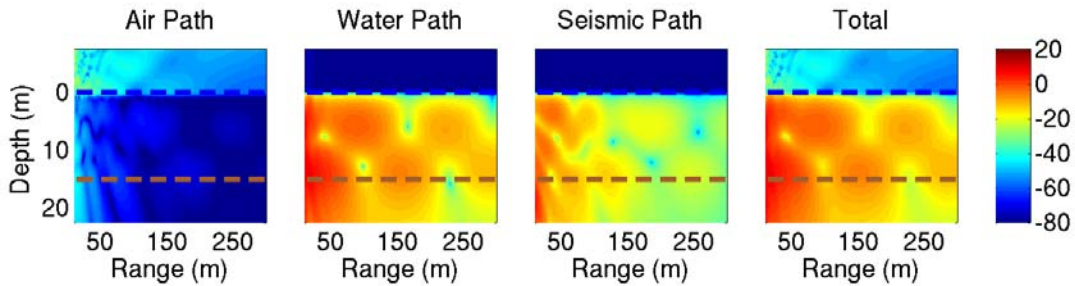
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Rubatex (4 inch), 200 Hz

pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



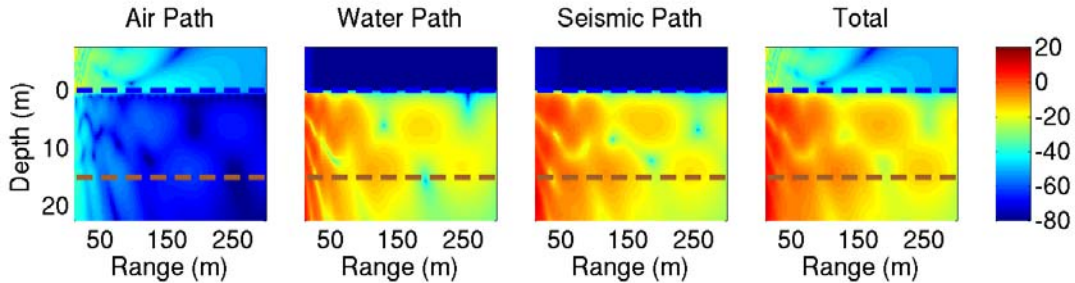
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Rubatex (8 inch), 200 Hz

pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



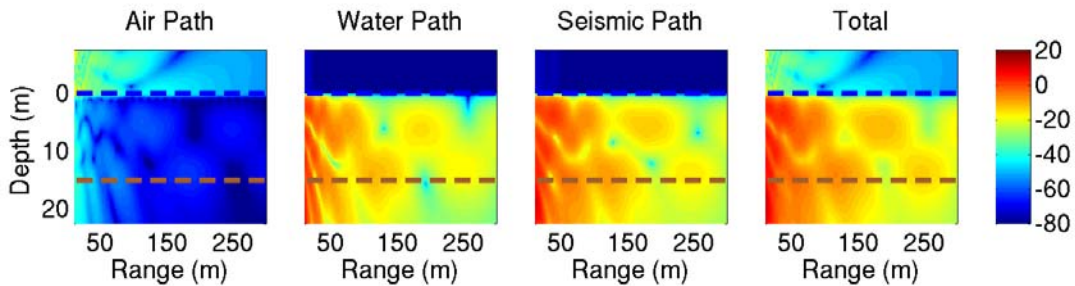
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Cofferdam (type 1), 200 Hz

pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m

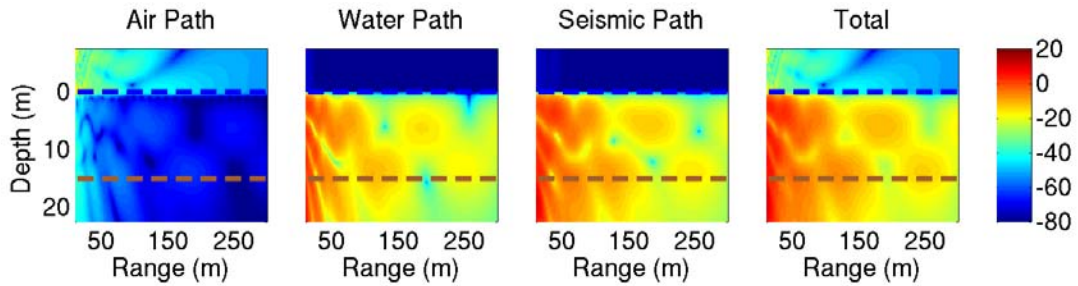


Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Cofferdam (type 2), 200 Hz

pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m

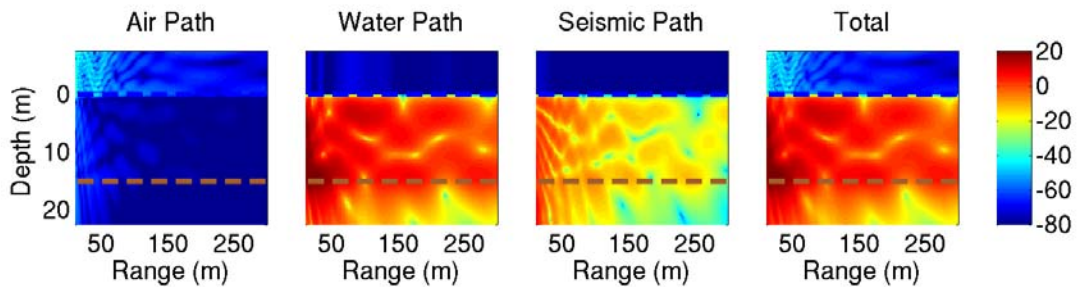


Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Cofferdam (type 3), 200 Hz
 pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m

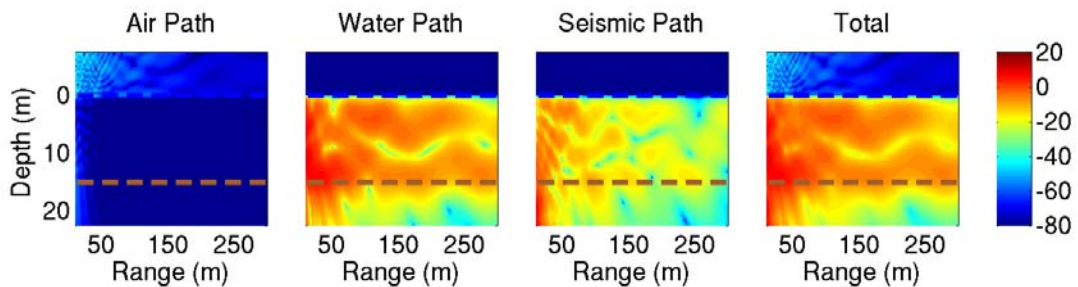


400 Hz:

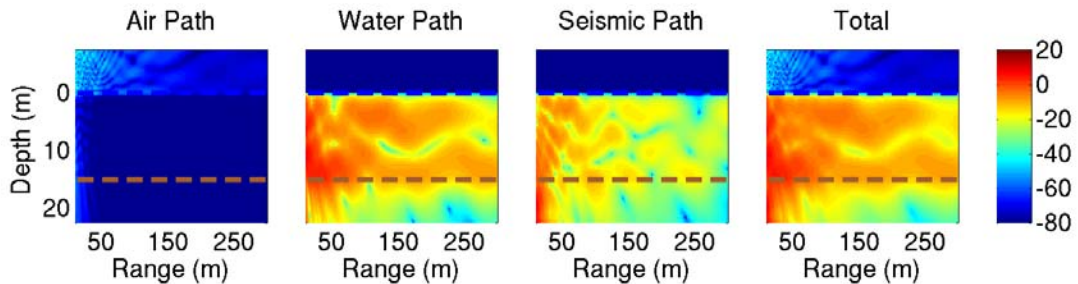
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Untreated, 400 Hz
 pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



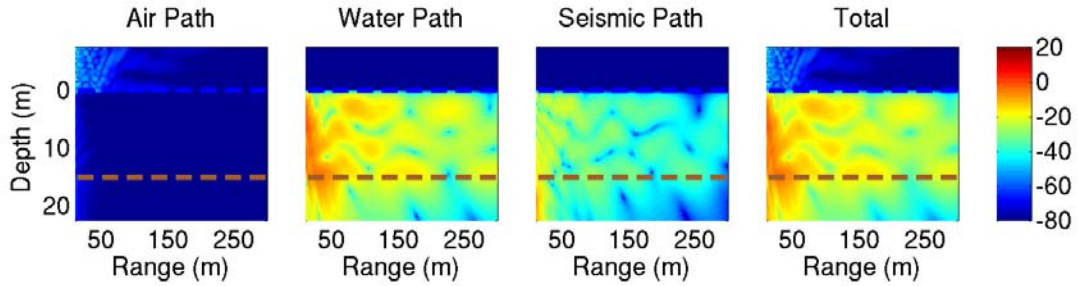
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Bubble screen (2.5 %), 400 Hz
 pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



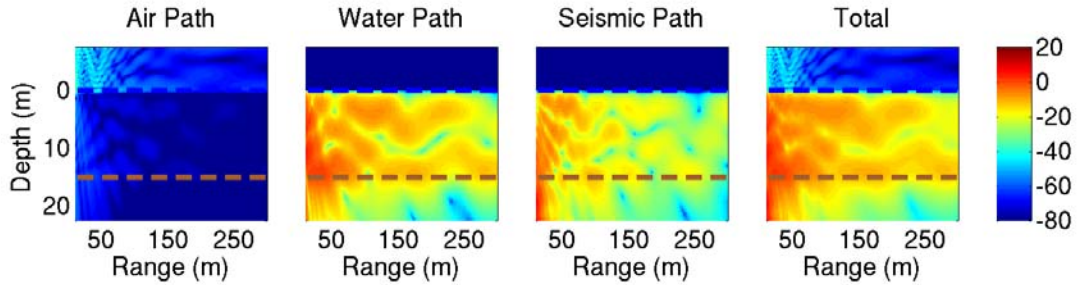
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Bubble screen (5 %), 400 Hz
 pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



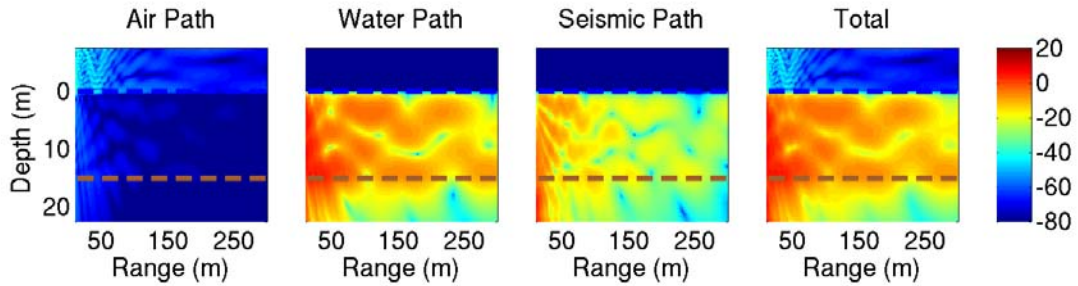
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Rubatex (2 inch), 400 Hz
 pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



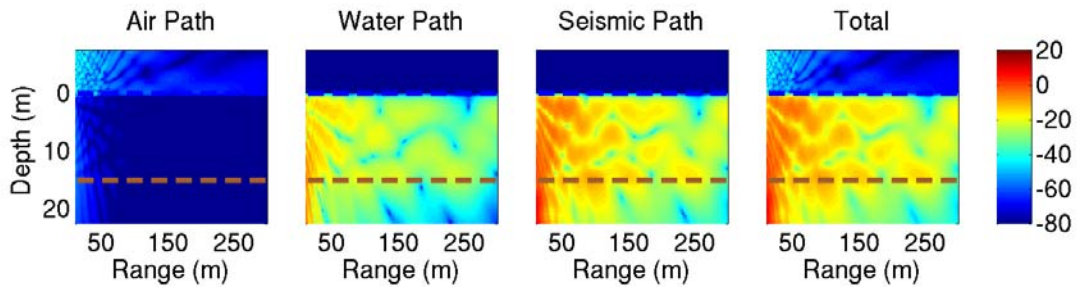
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Rubatex (4 inch), 400 Hz
 pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



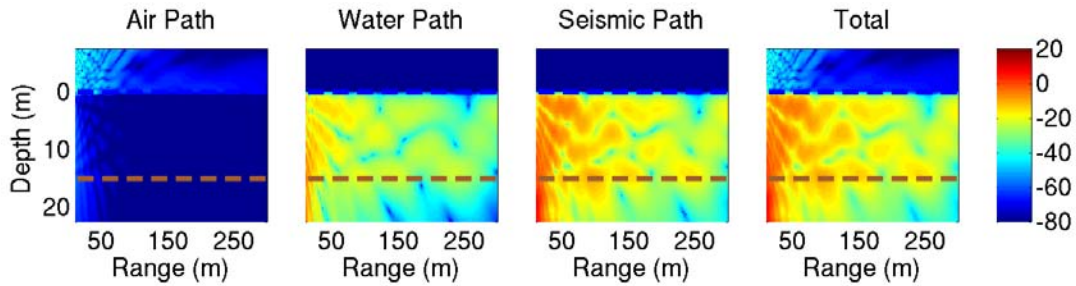
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Rubatex (8 inch), 400 Hz
 pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



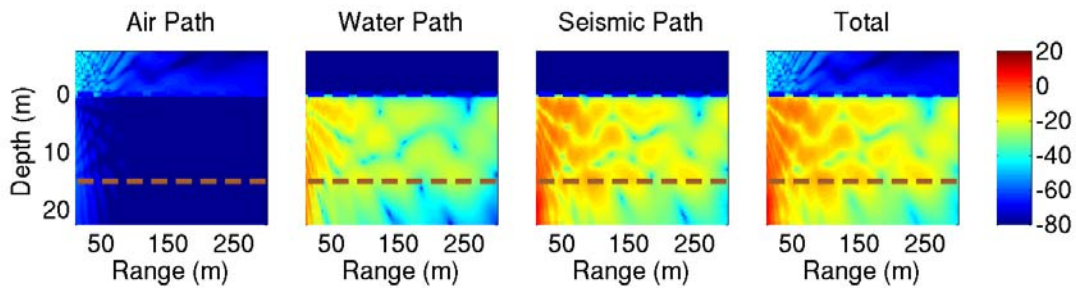
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Cofferdam (type 1), 400 Hz
 pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Cofferdam (type 2), 400 Hz
 pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m

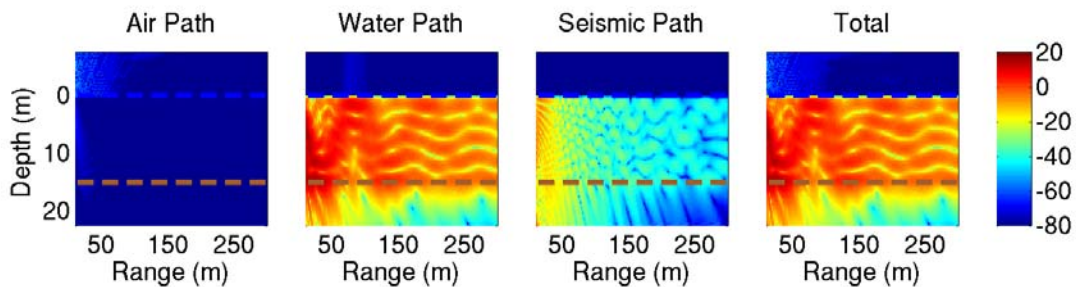


Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Cofferdam (type 3), 400 Hz
 pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m

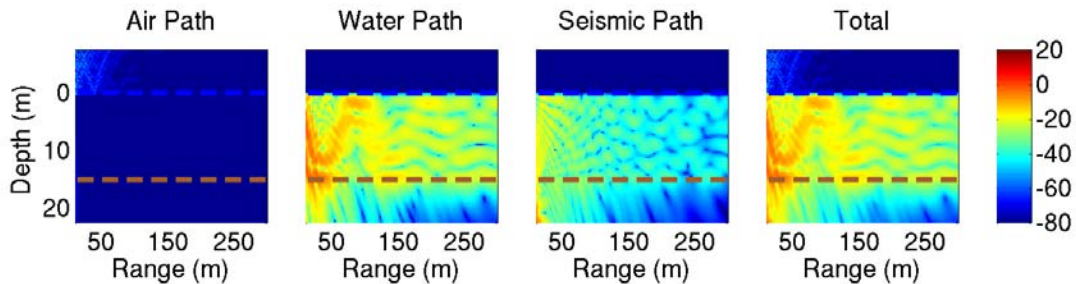


800 Hz:

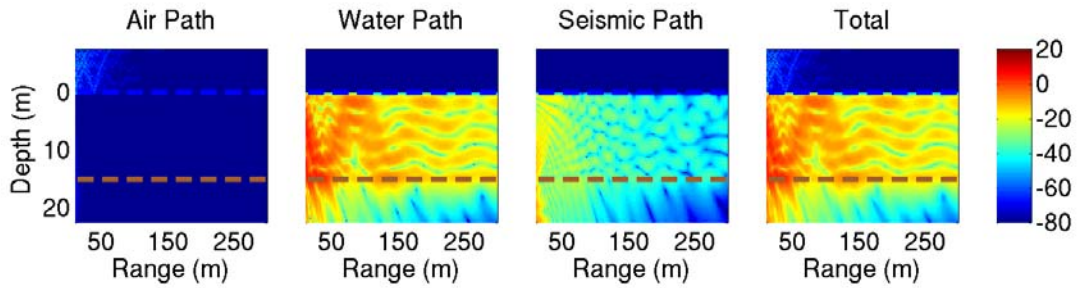
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Untreated, 800 Hz
 pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



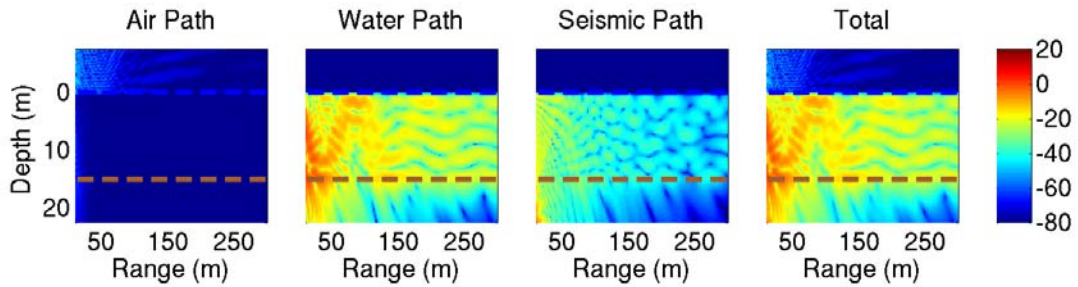
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Bubble screen (2.5 %), 800 Hz
 pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



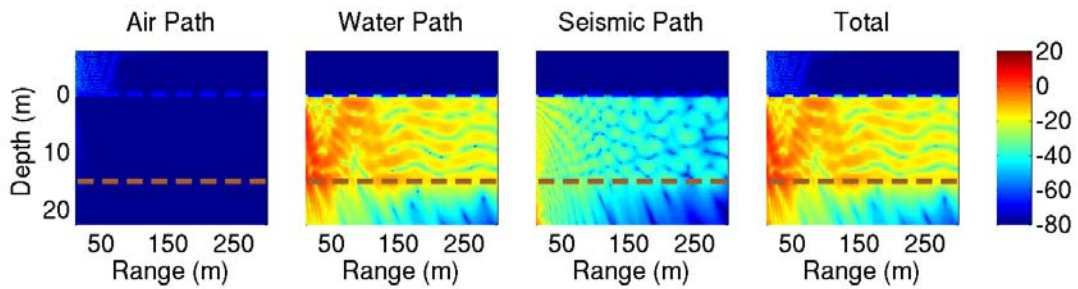
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Bubble screen (5 %), 800 Hz
 pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



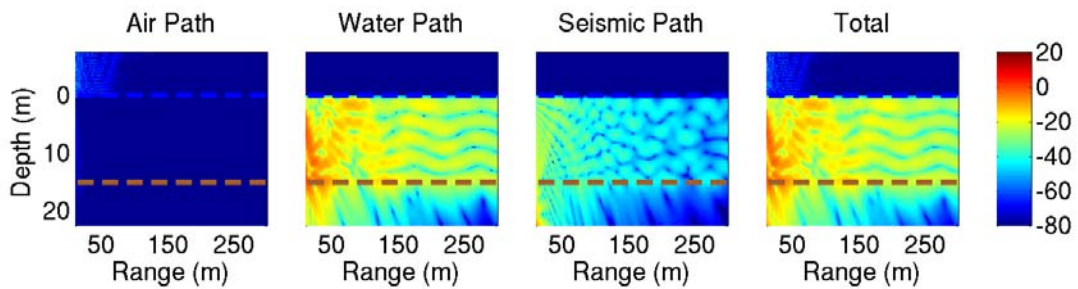
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Rubatex (2 inch), 800 Hz
 pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



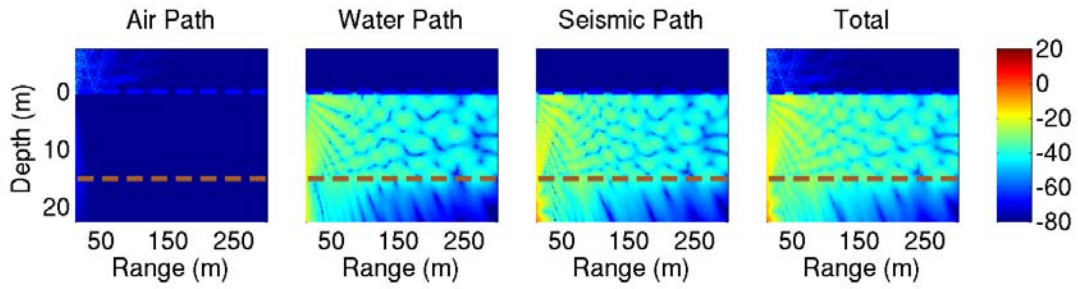
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Rubatex (4 inch), 800 Hz
 pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



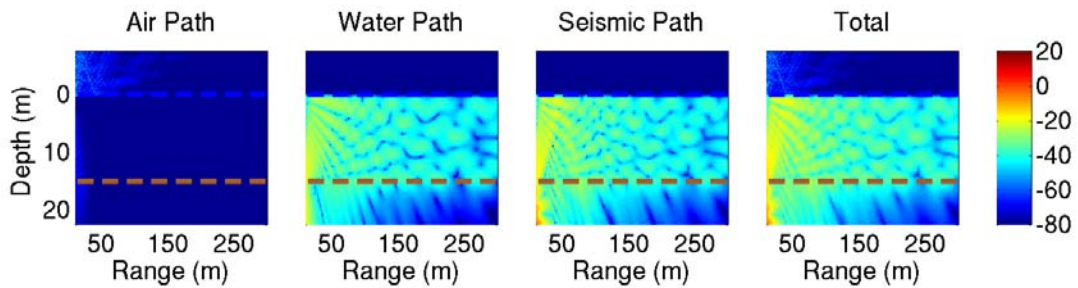
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Rubatex (8 inch), 800 Hz
 pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



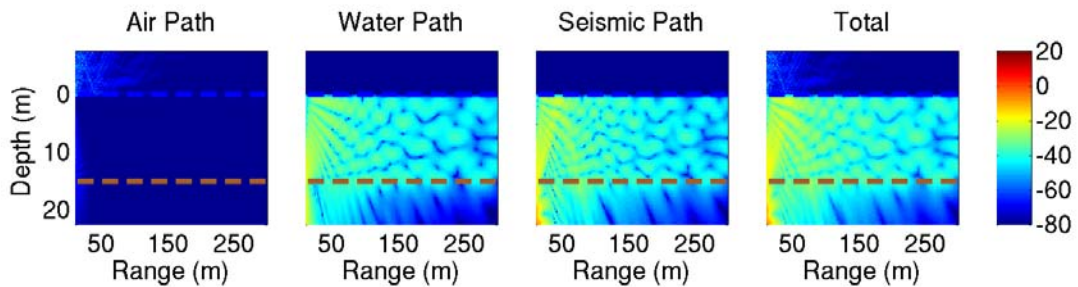
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Cofferdam (type 1), 800 Hz
 pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Cofferdam (type 2), 800 Hz
 pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Cofferdam (type 3), 800 Hz
 pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m

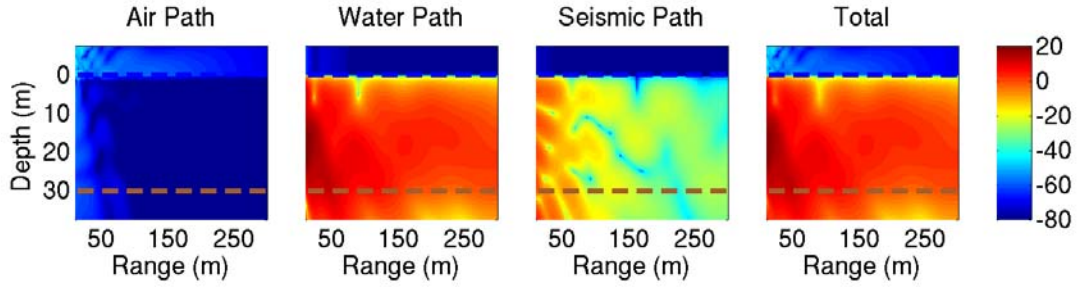


30 Meter Ocean Depth

100 Hz:

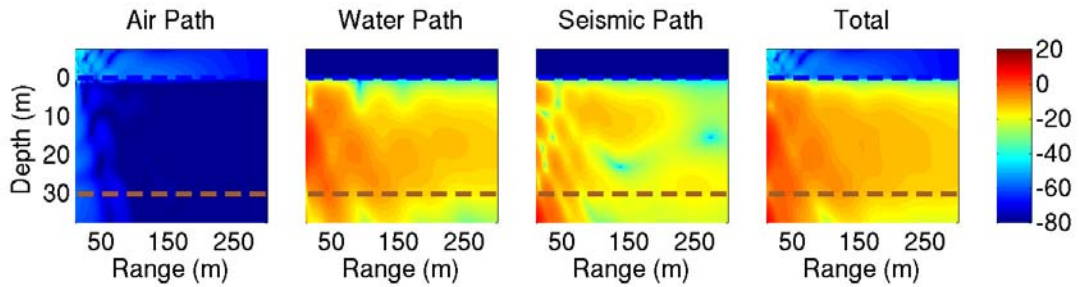
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Untreated, 100 Hz

pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



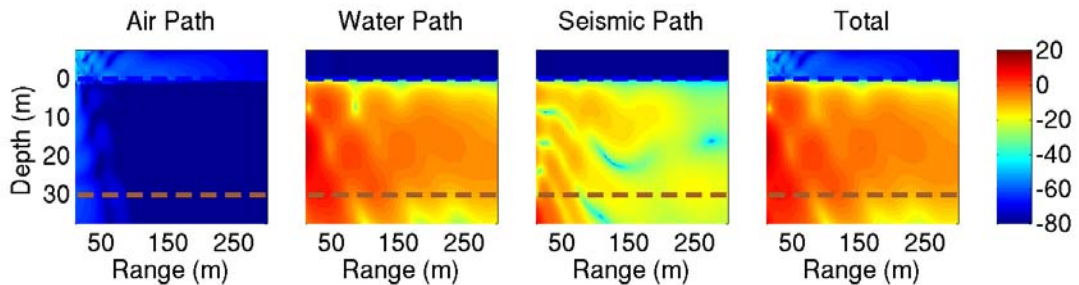
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Bubble screen (5 %), 100 Hz

pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m

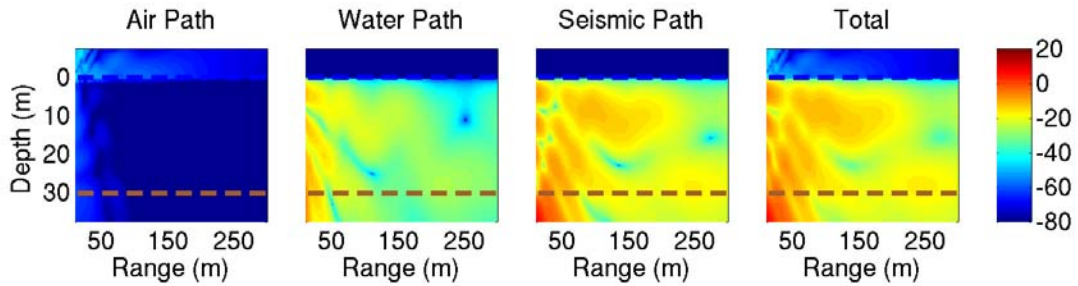


Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Rubatex (4 inch), 100 Hz

pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m

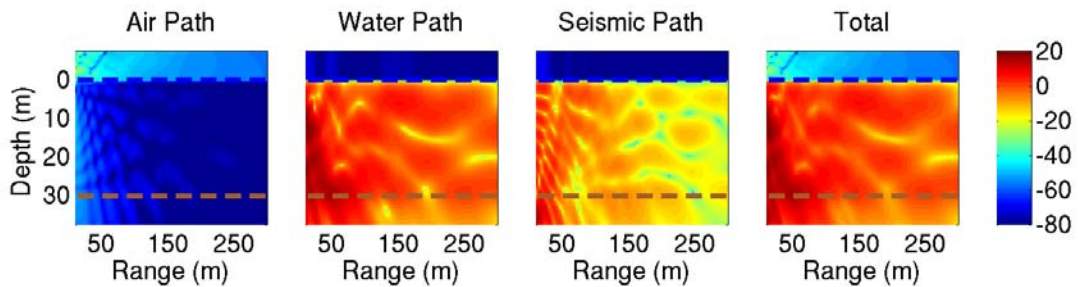


Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Cofferdam (type 2), 100 Hz
 pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m

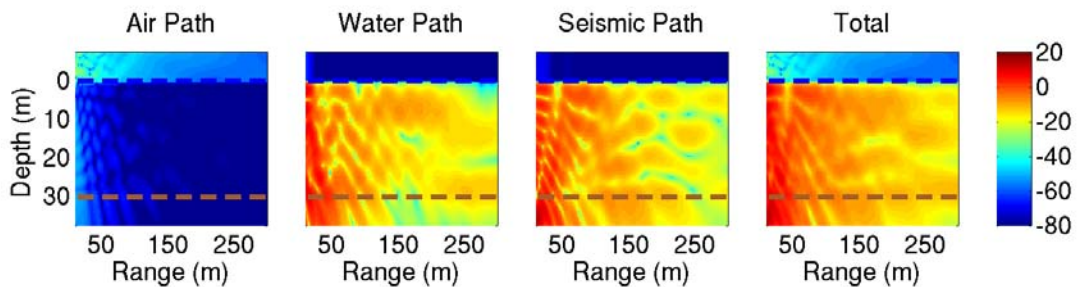


200 Hz:

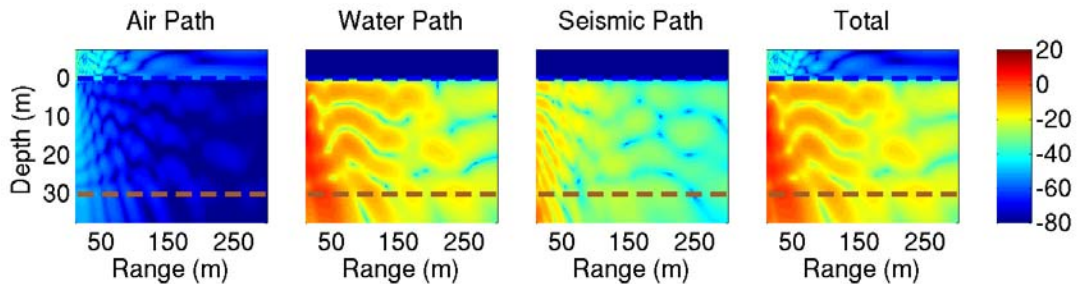
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Untreated, 200 Hz
 pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



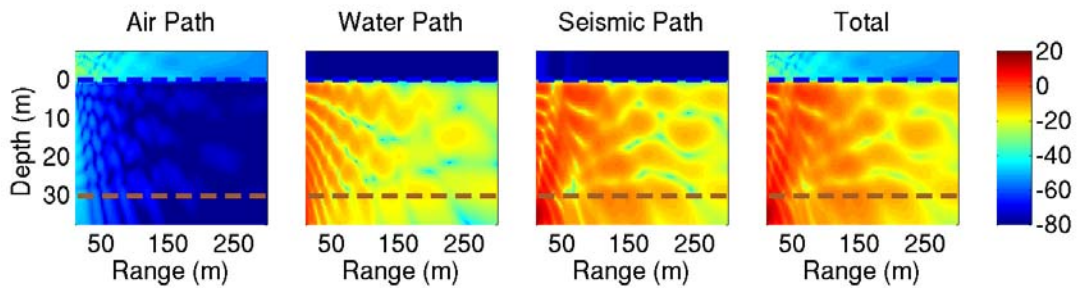
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Bubble screen (5 %), 200 Hz
 pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Rubatex (4 inch), 200 Hz
 pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m

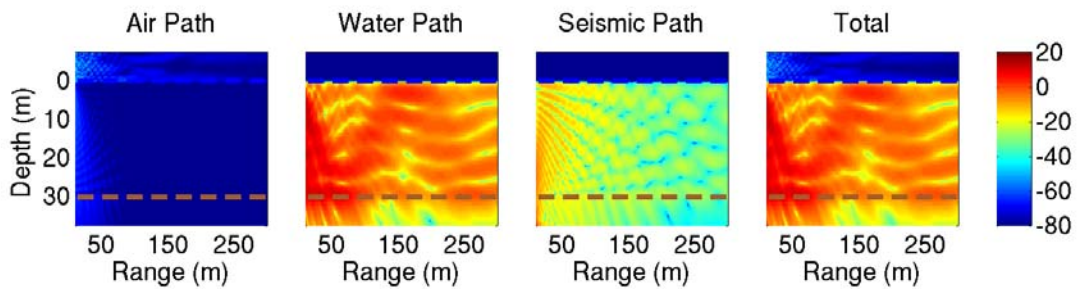


Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Cofferdam (type 2), 200 Hz
 pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m

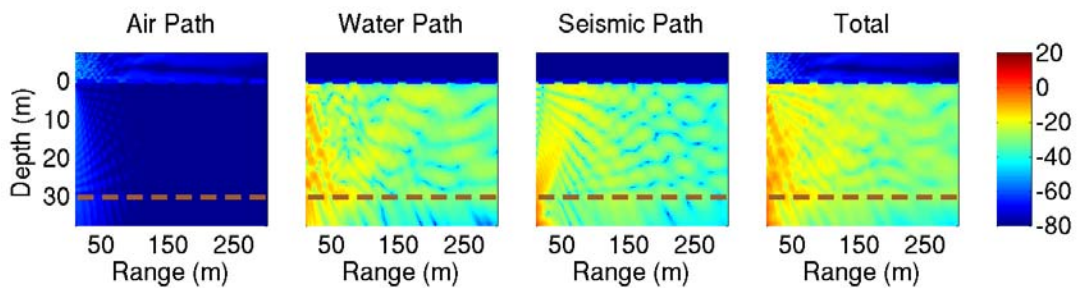


400 Hz:

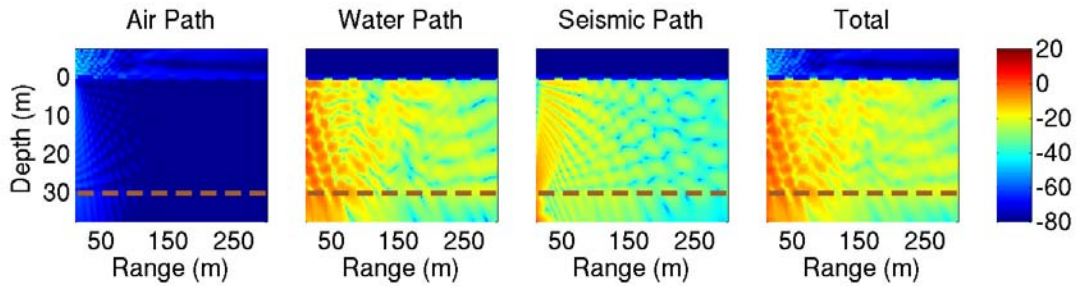
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Untreated, 400 Hz
 pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



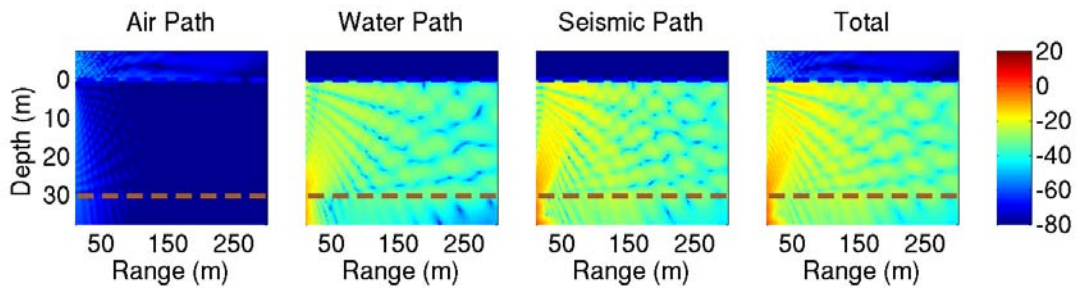
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Bubble screen (5 %), 400 Hz
 pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Rubatex (4 inch), 400 Hz
 pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m

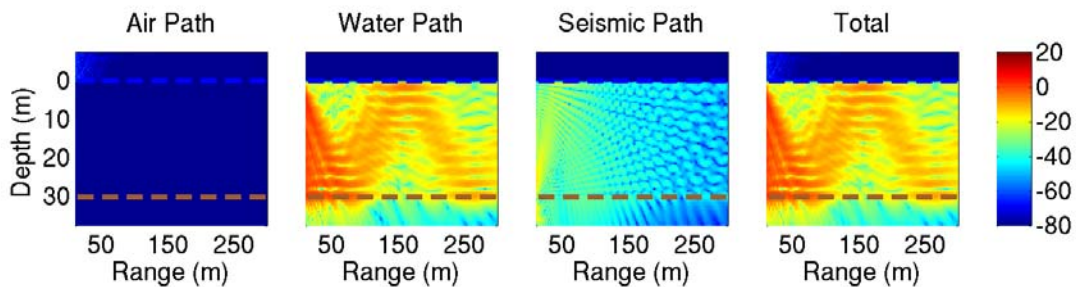


Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Cofferdam (type 2), 400 Hz
 pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m

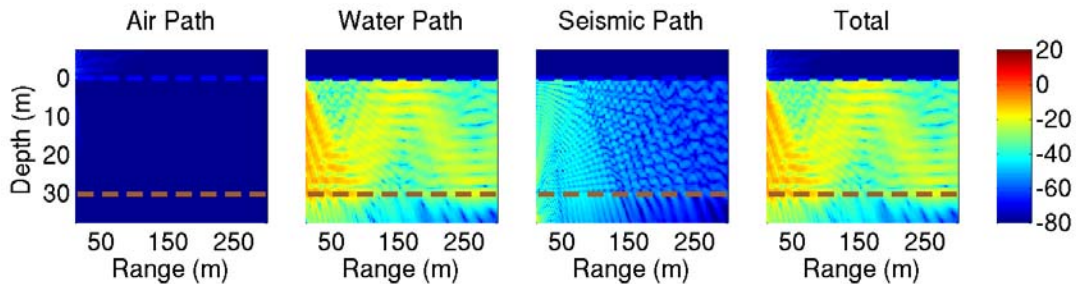


800 Hz:

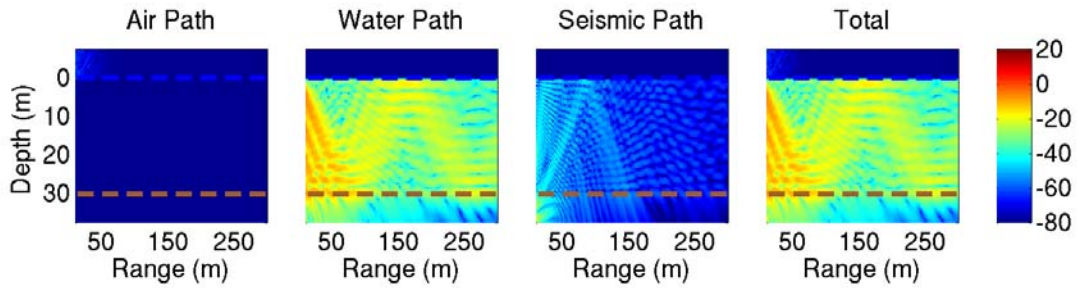
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Untreated, 800 Hz
 pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



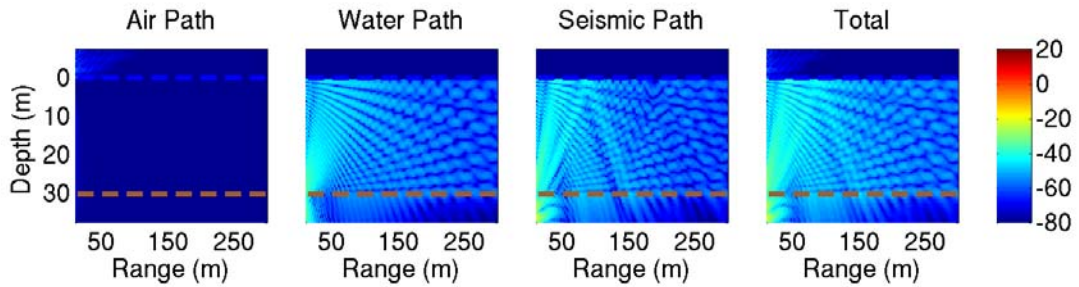
Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Bubble screen (5 %), 800 Hz
 pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Rubatex (4 inch), 800 Hz
pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



Transfer Function versus Range and Depth (dB re: 1uPa per lbf) : Cofferdam (type 2), 800 Hz
pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



B. Transfer Function at a Specific Depth and Range

The following figures provide transfer function at a specific depth and range, as a function of frequency, calculated at a range of 30m from the pile. Results are provided for locations 1m below the ocean surface, mid water column, and 1m above the ocean bottom. As noted in the color-scaled plots of transfer function versus range and depth, the sound field varies considerably as a function of position, so the results are averaged over a 1m cube. These results are representative of measurements conducted with a hydrophone during actual pile driving operations.

The plots provide results for the pile at initial contact with the bottom, halfway driven, and fully driven, to illustrate the impact of driven depth. For the 15m water depth cases, the halfway driven plots contain data for the all treatments considered. The 15m plots for initial contact and fully driven shows the transfer function as a function of frequency for the untreated option, 5% bubble screen, and the 4 inch Rubatex. For the 30m water depth cases, the halfway driven plots contain data for the untreated option, 5% bubble screen, the 4 inch Rubatex, and the cofferdam (with water filled pile). The 30m plots for initial contact and fully driven shows the transfer function as a function of frequency for the untreated option.

These show that levels can vary significantly with depth, in some cases by 15 dB or more. These also show some variation with pile driven depth. In many cases, the differences are small, but at some frequencies for some configurations the difference is over 5 dB.

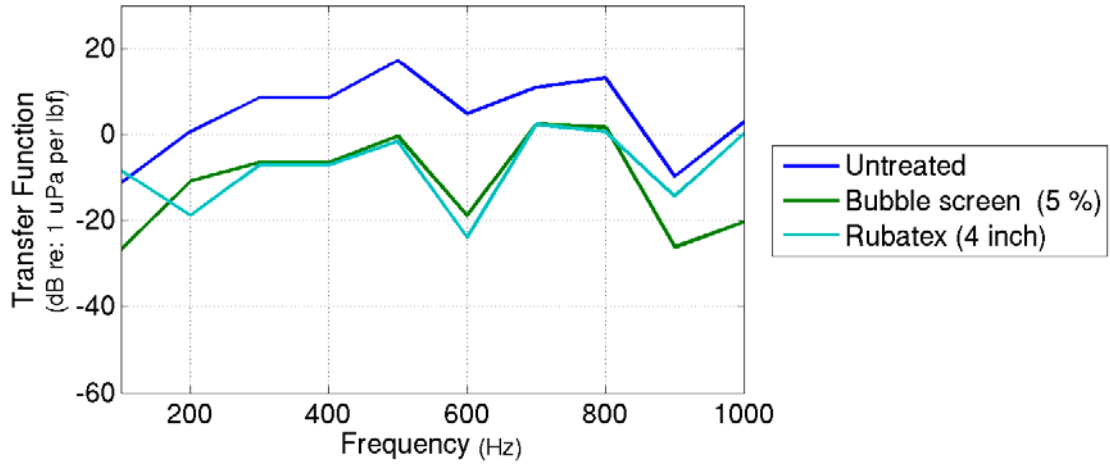
These illustrate the effect of the various treatments for the position modeled. As discussed above, the depth-averaged results are a better overall metric for comparing the effectiveness of treatments, but these plots illustrate the variability that can be expected with water depth that would be observable in measurements of actual pile driving events. These plots show consistent improvements in the underwater sound level resulting from the various treatments, with the greatest reduction generally provided by the cofferdam, which is consistent with the overall findings discussed above.

15 Meter Ocean Depth

1 meter below the surface:

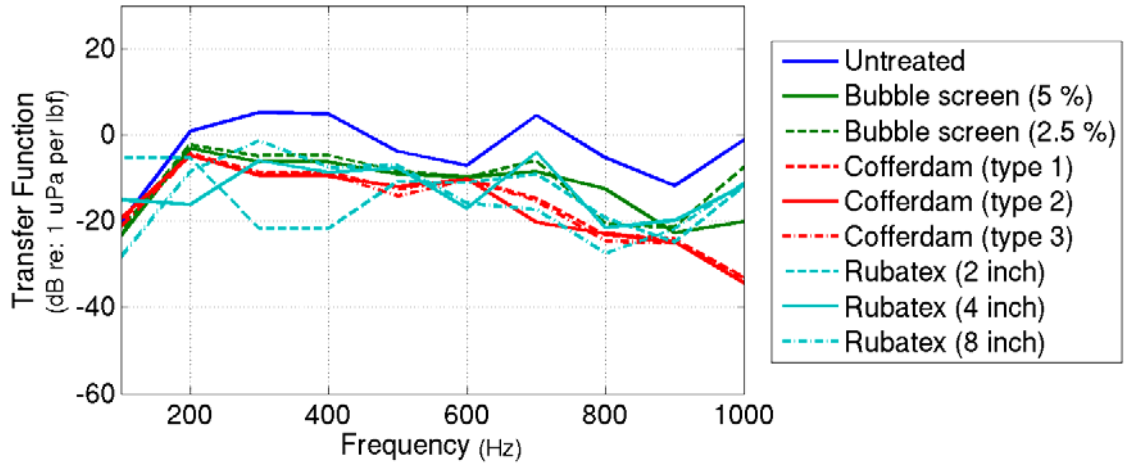
Transfer Function versus Frequency (1 m below the surface, 30 m range)

pile diameter: 5.5 m, seafloor depth: 15 m, pile penetration into seafloor: 0 m



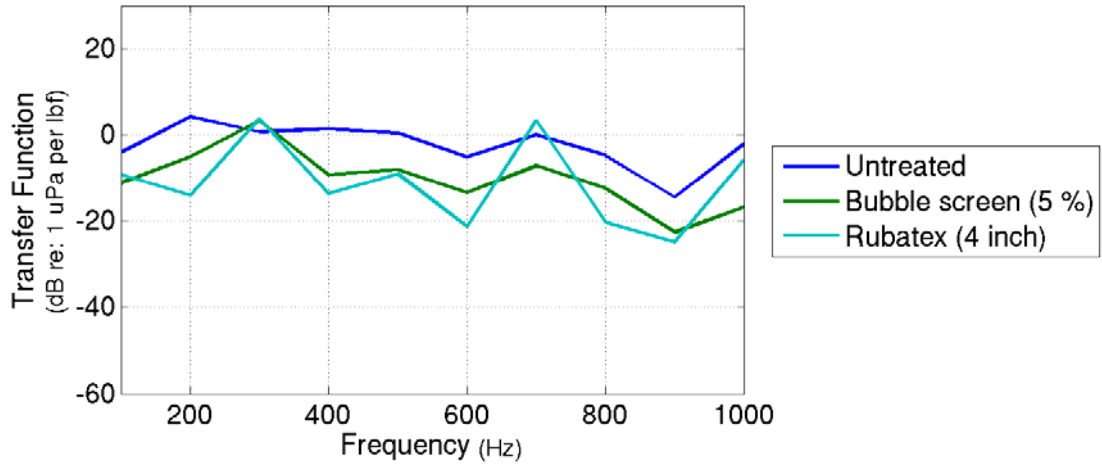
Transfer Function versus Frequency (1 m below the surface, 30 m range)

pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



Transfer Function versus Frequency (1 m below the surface, 30 m range)

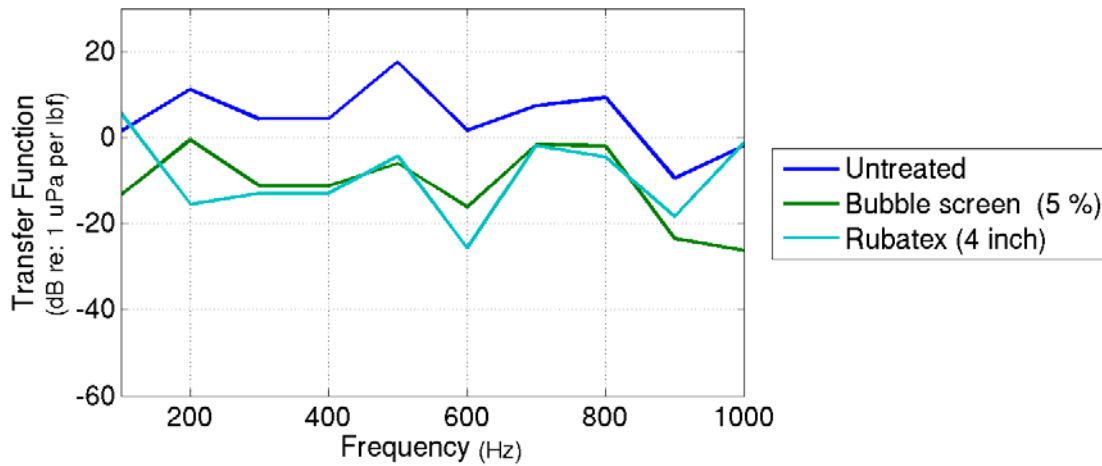
pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 26 m



Mid water column:

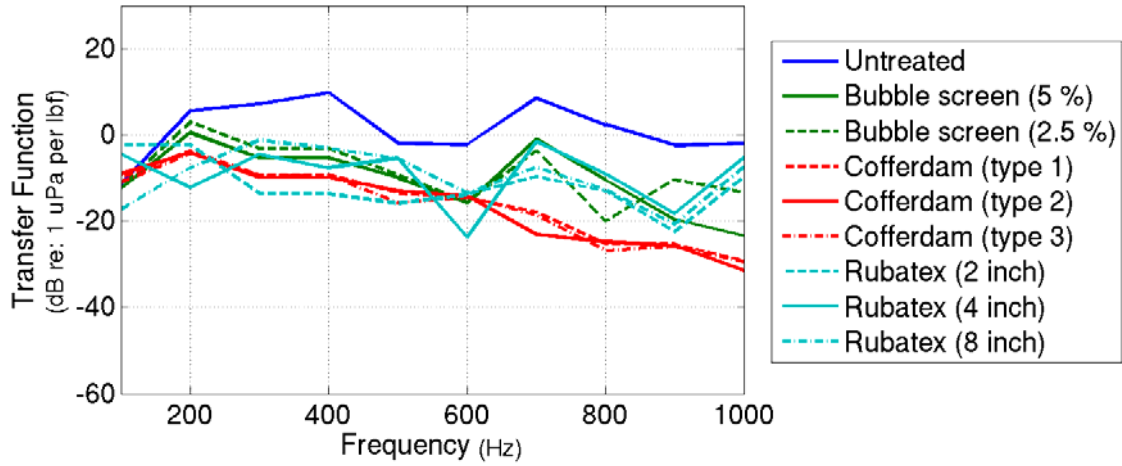
Transfer Function versus Frequency (mid-water column, 30 m range)

pile diameter: 5.5 m, seafloor depth: 15 m, pile penetration into seafloor: 0 m



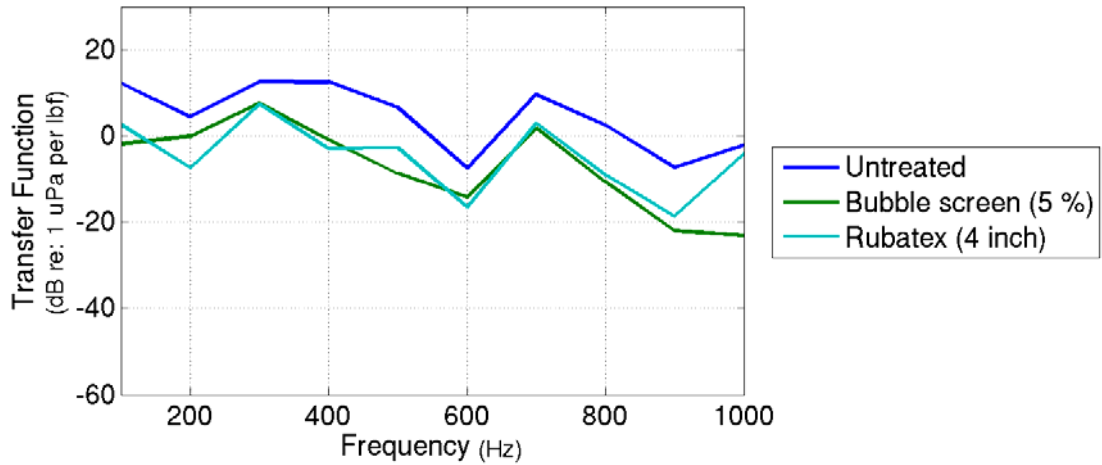
Transfer Function versus Frequency (mid-water column, 30 m range)

pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



Transfer Function versus Frequency (mid-water column, 30 m range)

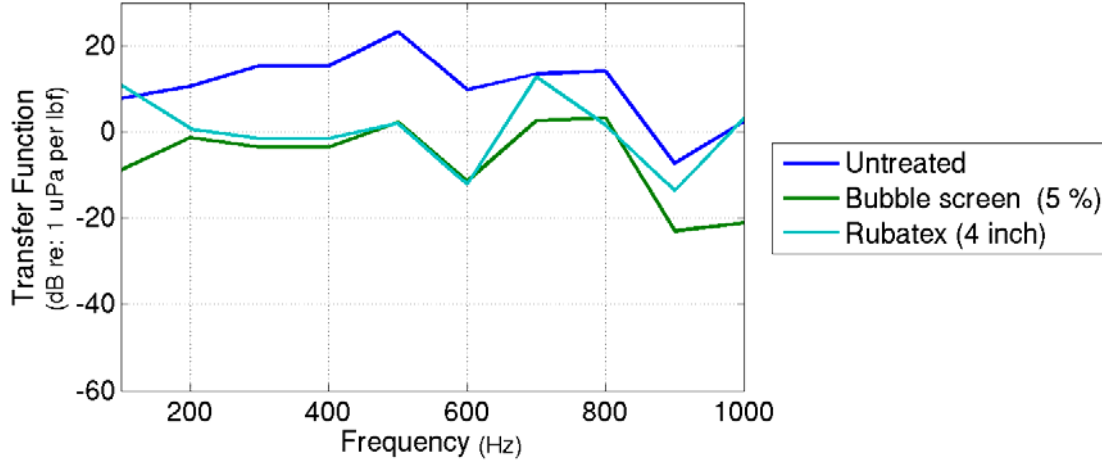
pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 26 m



1 meter above the ocean bottom:

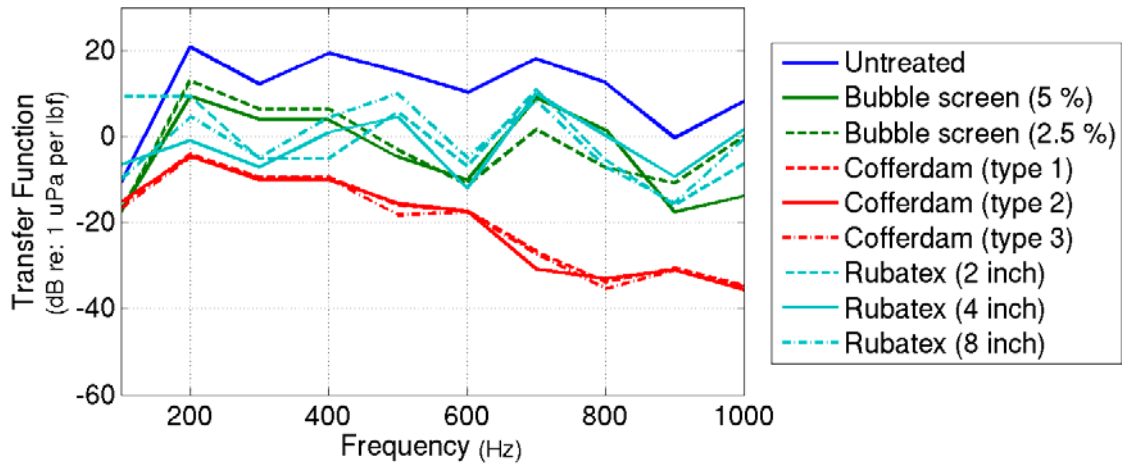
Transfer Function versus Frequency (1 m above seafloor, 30 m range)

pile diameter: 5.5 m, seafloor depth: 15 m, pile penetration into seafloor: 0 m



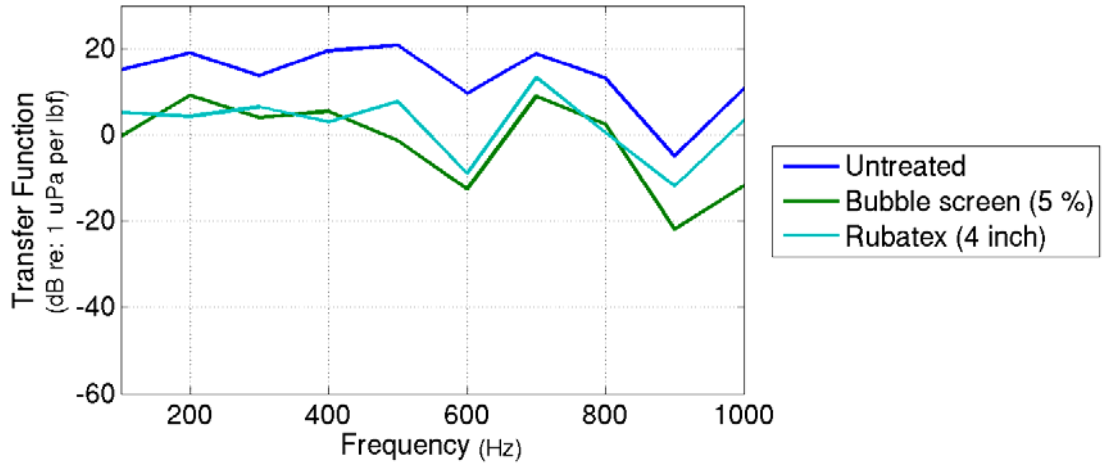
Transfer Function versus Frequency (1 m above seafloor, 30 m range)

pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



Transfer Function versus Frequency (1 m above seafloor, 30 m range)

pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 26 m

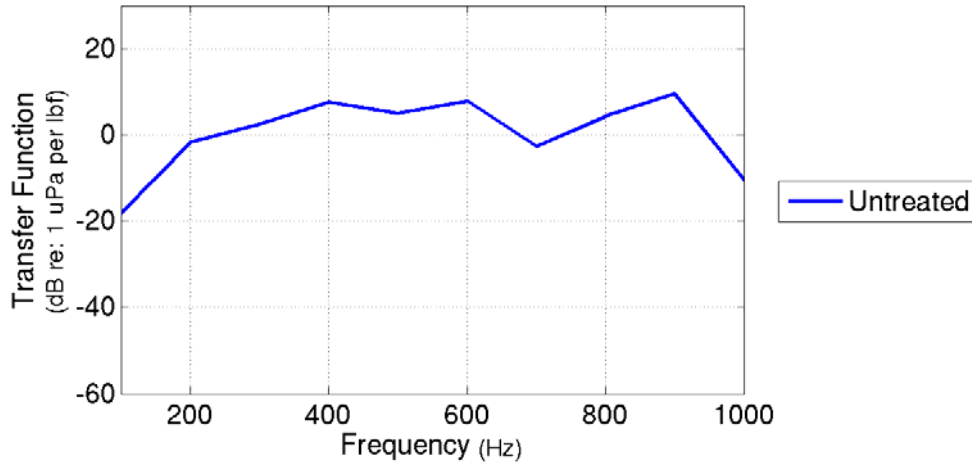


30 Meter Ocean Depth

1 meter below the surface:

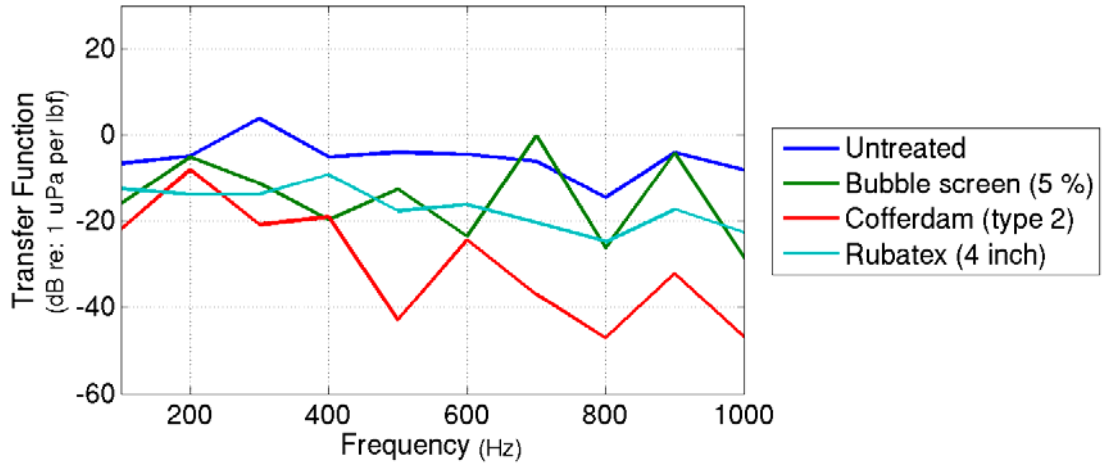
Transfer Function versus Frequency (1 m below the surface, 30 m range)

pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 0 m



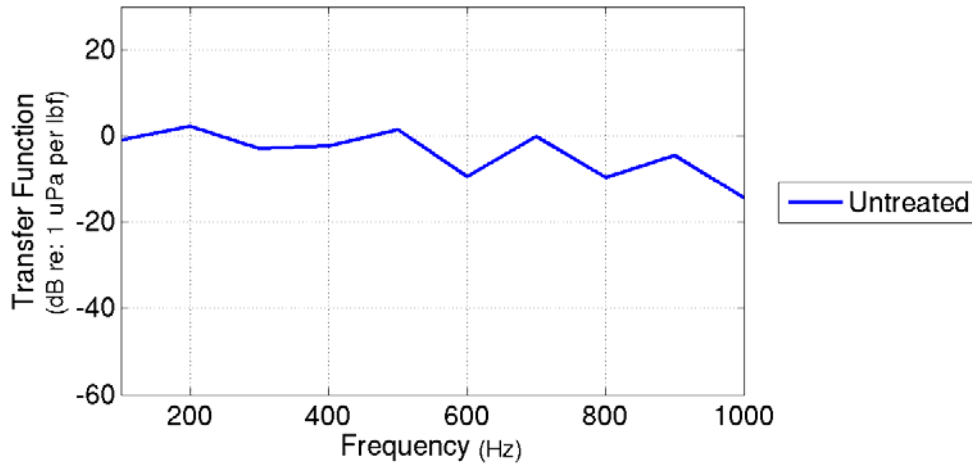
Transfer Function versus Frequency (1 m below the surface, 30 m range)

pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



Transfer Function versus Frequency (1 m below the surface, 30 m range)

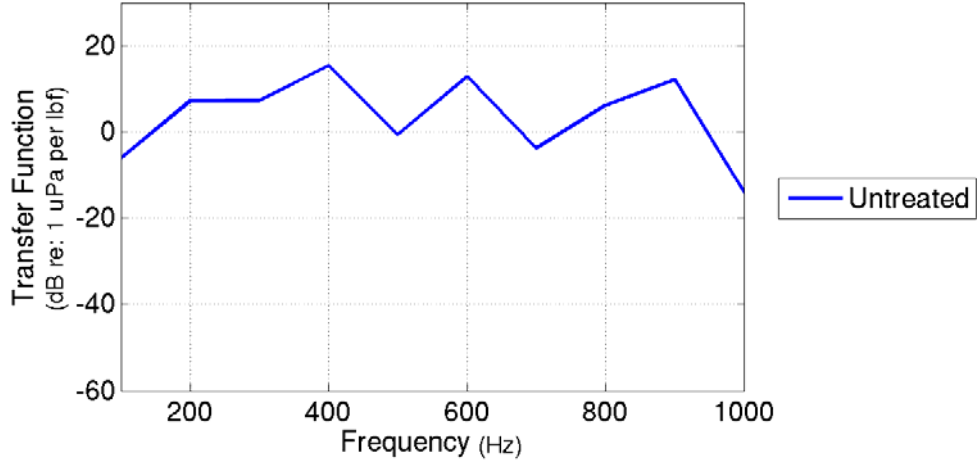
pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 35 m



Mid water column:

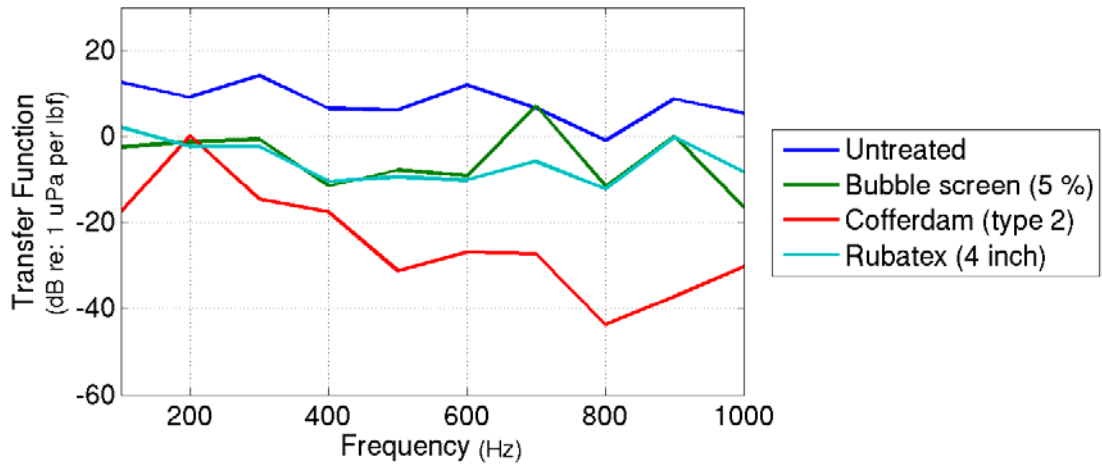
Transfer Function versus Frequency (mid-water column, 30 m range)

pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 0 m



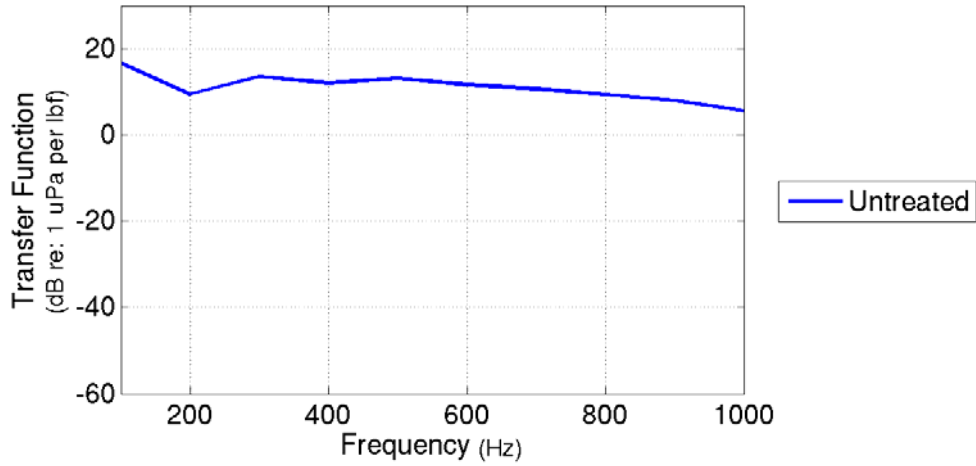
Transfer Function versus Frequency (mid-water column, 30 m range)

pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



Transfer Function versus Frequency (mid-water column, 30 m range)

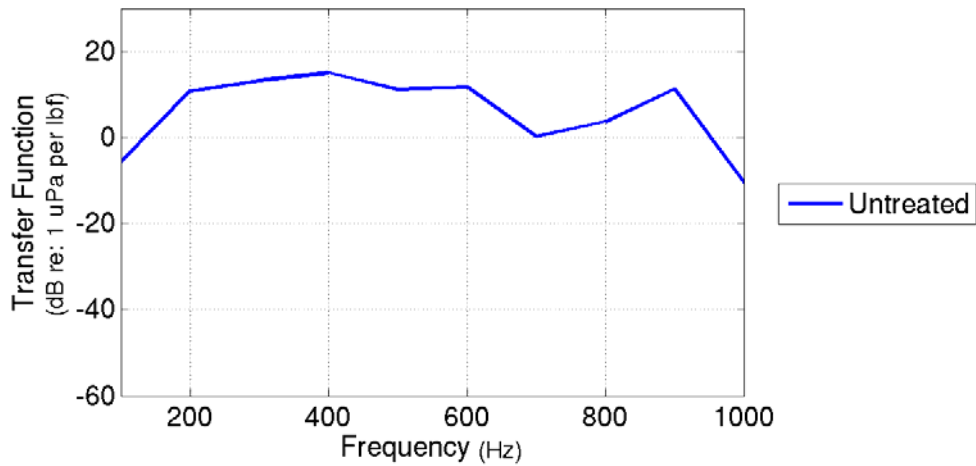
pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 35 m



1 meter above the ocean bottom:

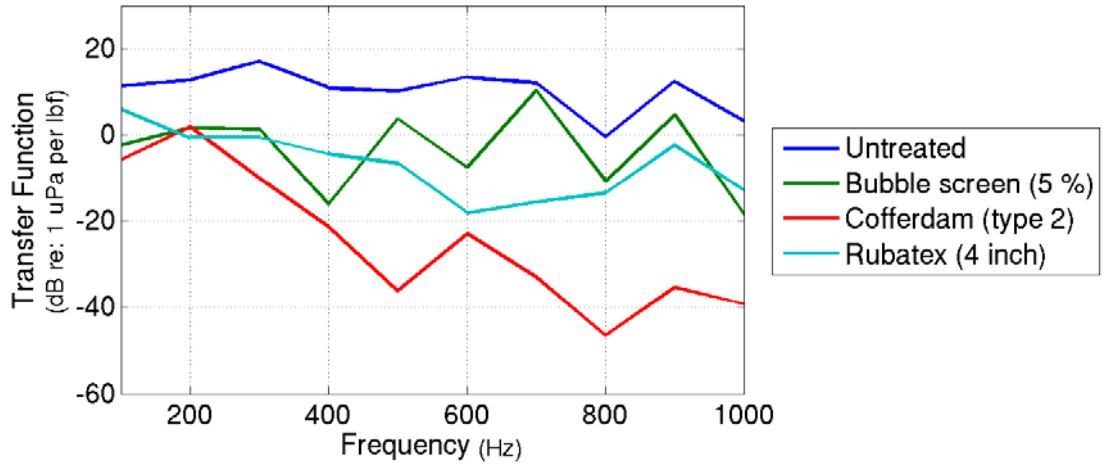
Transfer Function versus Frequency (1 m above seafloor, 30 m range)

pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 0 m



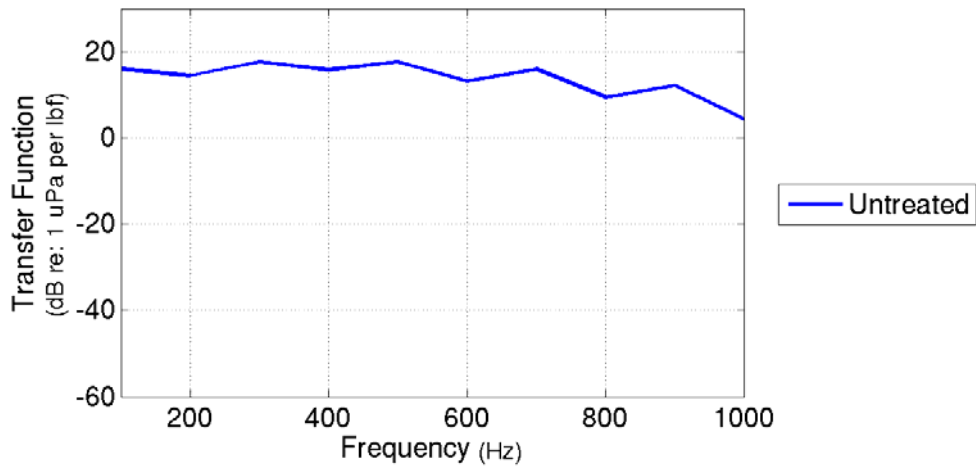
Transfer Function versus Frequency (1 m above seafloor, 30 m range)

pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



Transfer Function versus Frequency (1 m above seafloor, 30 m range)

pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 35 m



C. Depth Averaged Transfer Function as a Function of Frequency

The following figures provide transfer function, averaged over depth, at ranges of 10m, 100m, and 300m from the pile, as a function of frequency. These results are considered a better overall representation of treatment effect than the point data above.

The plots provide results for the pile at initial contact with the bottom, halfway driven, and fully driven, to illustrate the impact of driven depth. For the 15m water depth cases, the halfway driven plots contain data for the all treatments considered. The 15m plots for initial contact and fully driven shows the transfer function as a function of frequency for the untreated option, 5% bubble screen, and the 4 inch Rubatex. For the 30m water depth cases, the halfway driven plots contain data for the untreated option, 5% bubble screen, the 4 inch Rubatex, and the cofferdam (with water filled pile). The 30m plots for initial contact and fully driven shows the transfer function as a function of frequency for the untreated option.

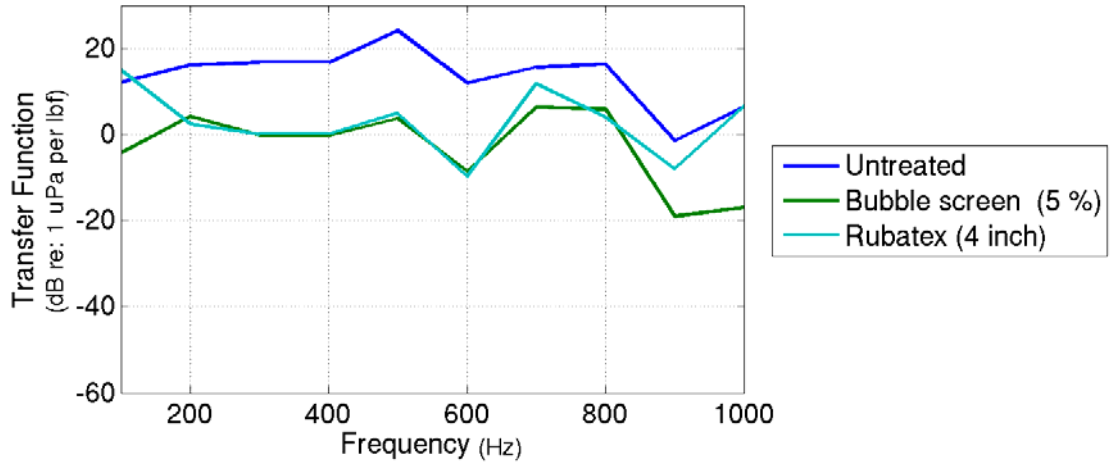
These show the impact of the noise mitigation options. The bubble screen and the Rubatex reduce the transfer function by very similar amounts, typically 10 to 15 dB for the 15m deep ocean. For the 30m deep ocean, the effect of the bubble screen and the Rubatex is typically around a 10 dB reduction, similar to 15m water. The 2.5% volume fraction air is not significantly different from 5% volume fraction. The 2 inch thick, 4 inch thick, and 8 inch thick Rubatex vary somewhat from each other at some frequencies, but not consistently, and overall the effectiveness of each is about the same. The variation of Rubatex performance with frequency is common at these frequencies, where the acoustic wavelength is much greater than the thickness of all three Rubatex cases. The cofferdam typically reduces the transfer function by 20 to 30 dB for the 15m deep ocean. For the 30m deep ocean, the effect of the cofferdam is typically a 20 to 40 dB reduction, similar to 15m water. As discussed above, this massive dewatered cofferdam is considered the upper bound on possible noise mitigation treatment performance.

15 Meter Ocean Depth

10 meter range from pile:

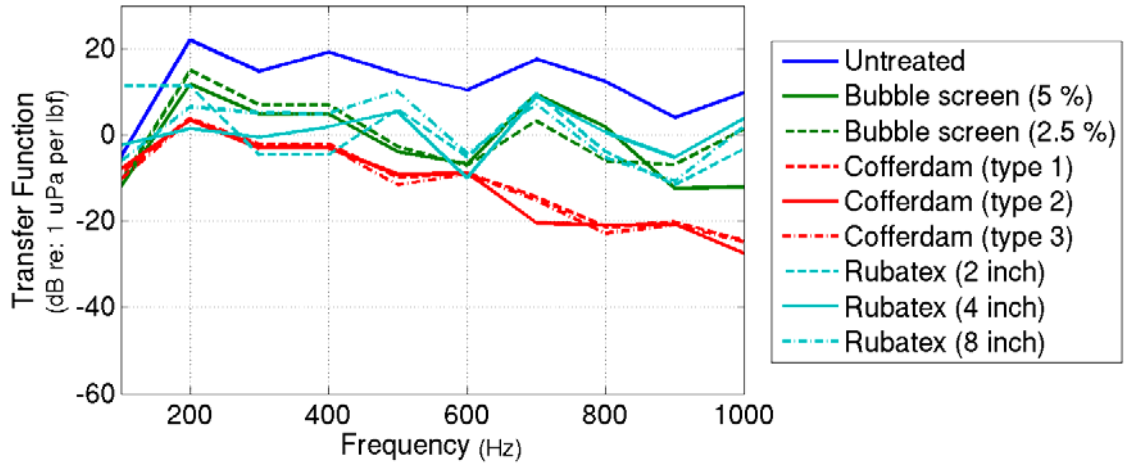
Depth-Averaged Transfer Function versus Frequency (10 m range)

pile diameter: 5.5 m, seafloor depth: 15 m, pile penetration into seafloor: 0 m



Depth-Averaged Transfer Function versus Frequency (10 m range)

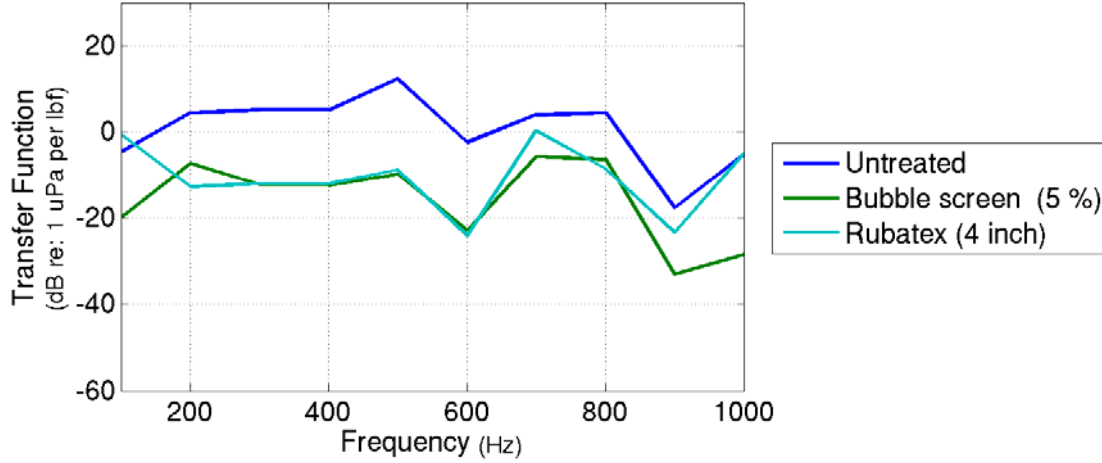
pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



100 meter range from pile:

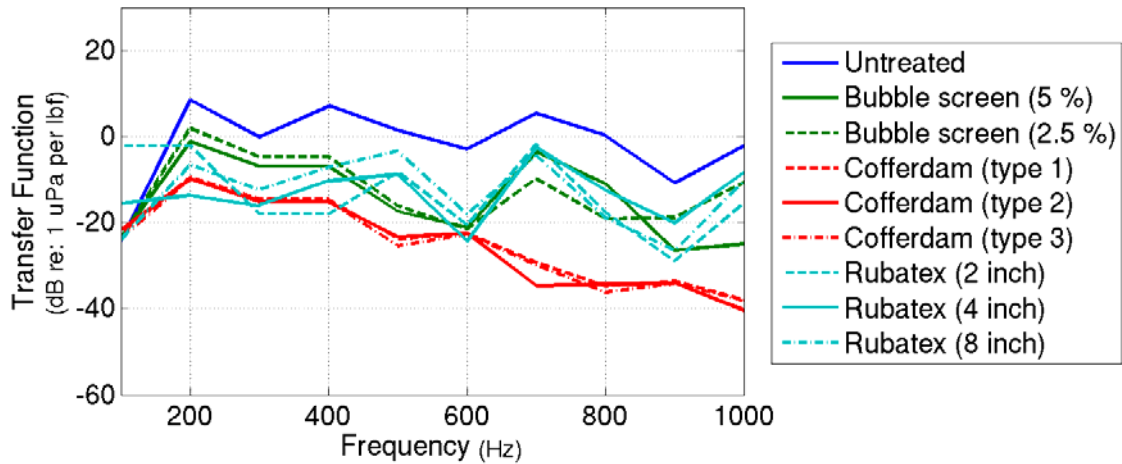
Depth-Averaged Transfer Function versus Frequency (100 m range)

pile diameter: 5.5 m, seafloor depth: 15 m, pile penetration into seafloor: 0 m



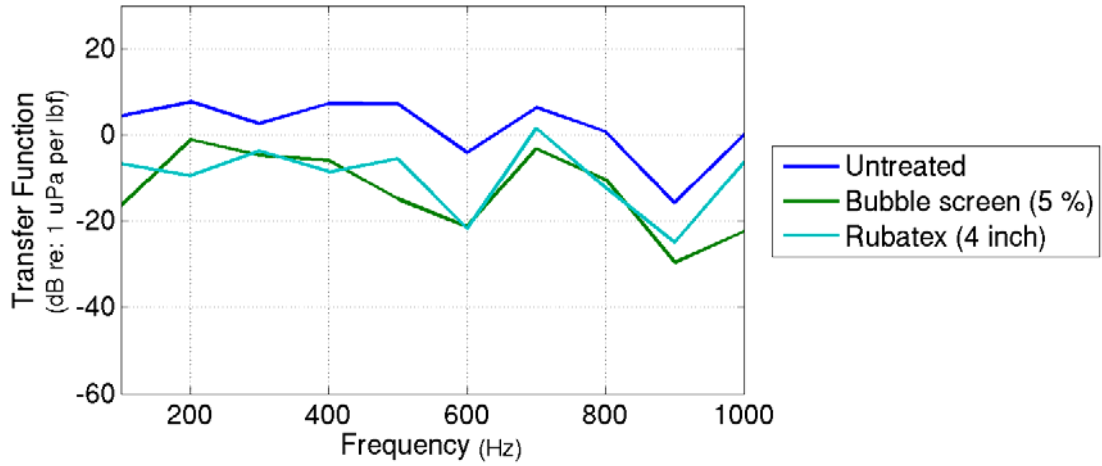
Depth-Averaged Transfer Function versus Frequency (100 m range)

pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



Depth-Averaged Transfer Function versus Frequency (100 m range)

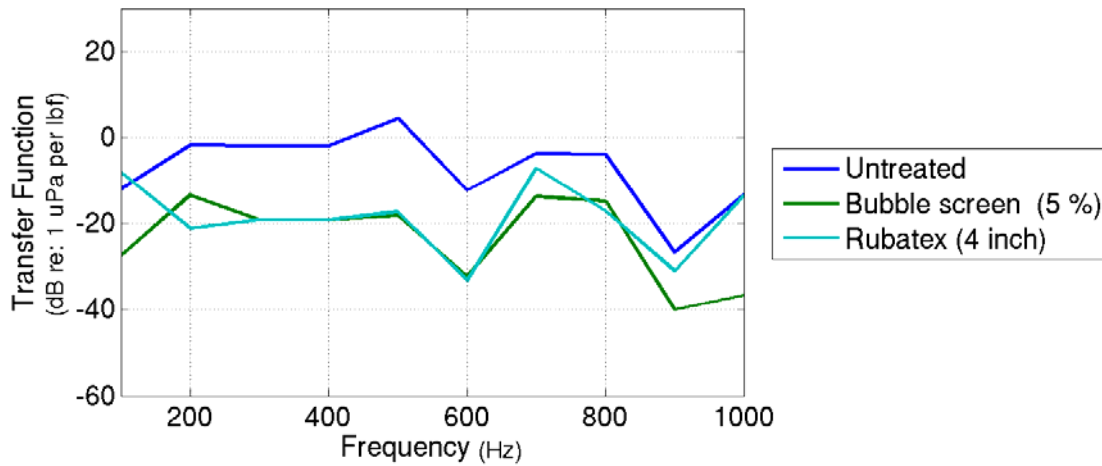
pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 26 m



300 meter range from pile:

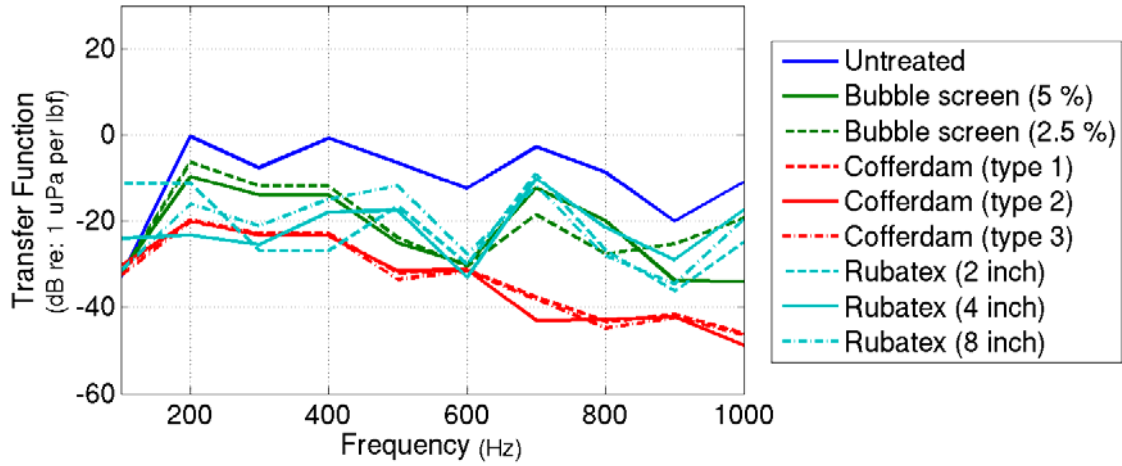
Depth-Averaged Transfer Function versus Frequency (300 m range)

pile diameter: 5.5 m, seafloor depth: 15 m, pile penetration into seafloor: 0 m



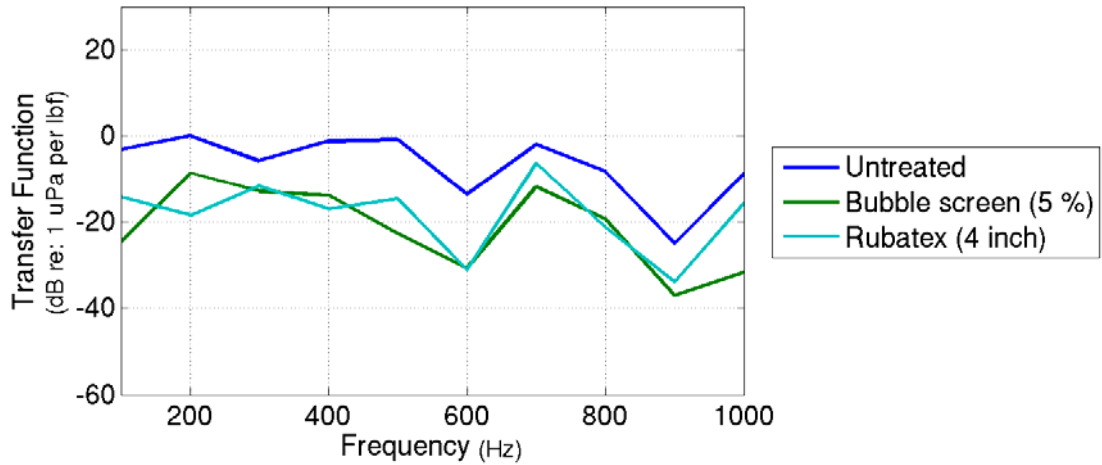
Depth-Averaged Transfer Function versus Frequency (300 m range)

pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



Depth-Averaged Transfer Function versus Frequency (300 m range)

pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 26 m

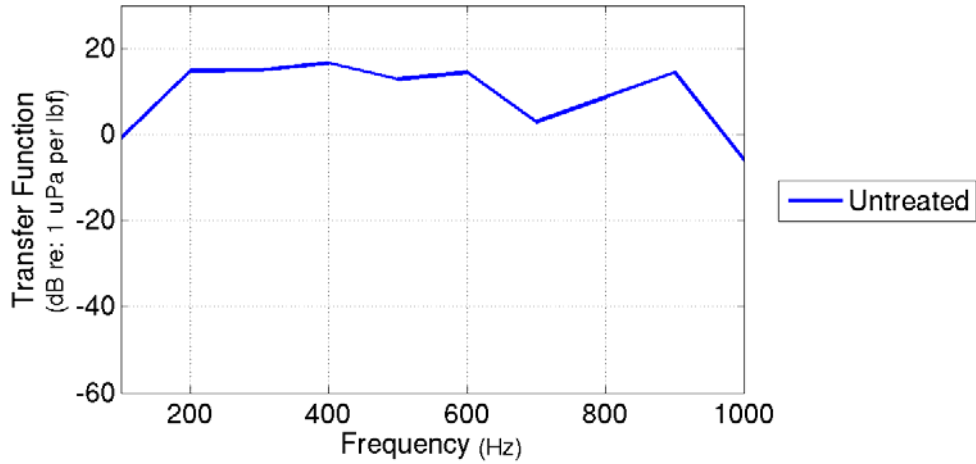


30 Meter Ocean Depth

10 meter range from pile:

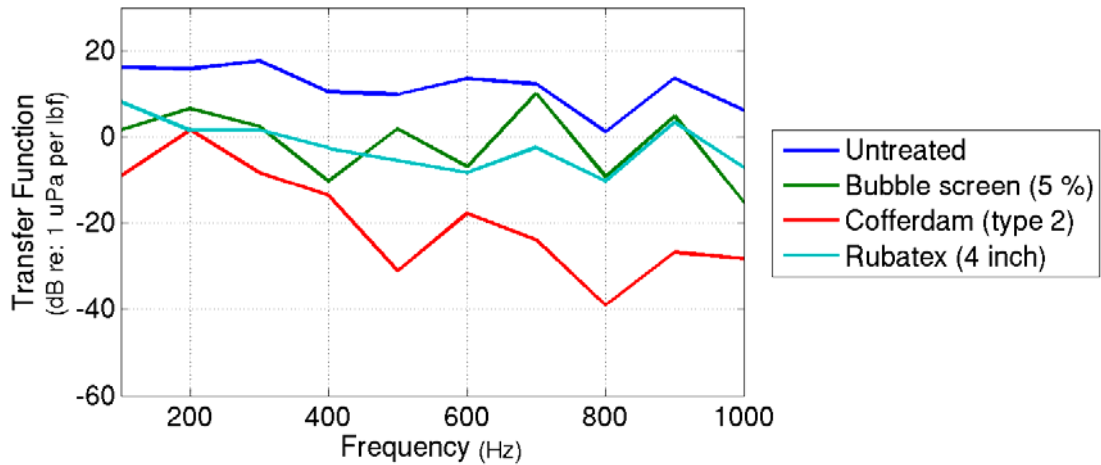
Depth-Averaged Transfer Function versus Frequency (10 m range)

pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 0 m



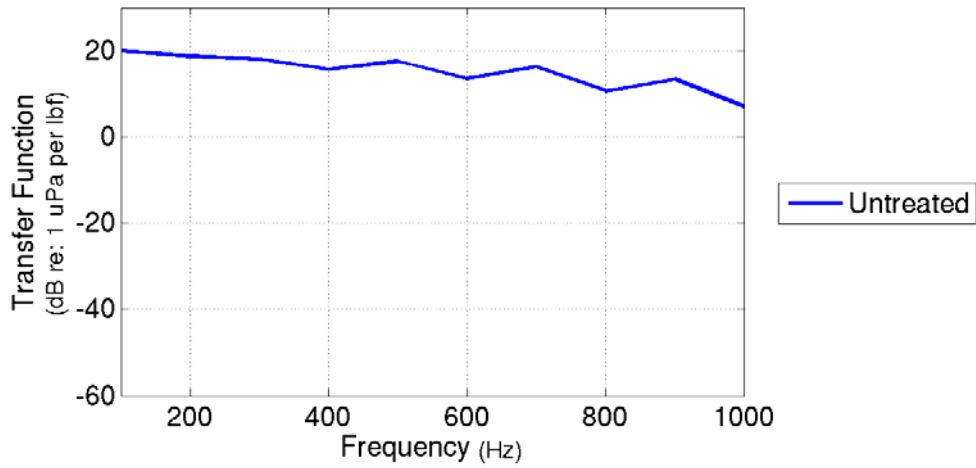
Depth-Averaged Transfer Function versus Frequency (10 m range)

pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



Depth-Averaged Transfer Function versus Frequency (10 m range)

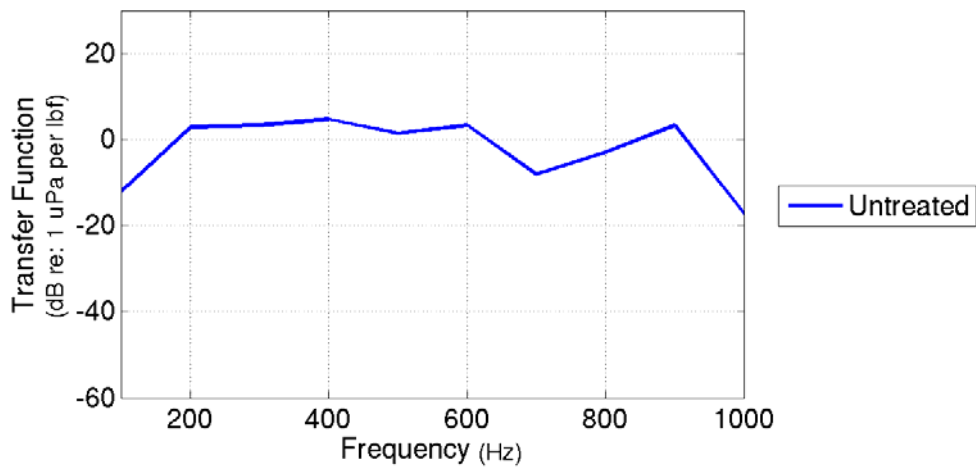
pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 35 m



100 meter range from pile:

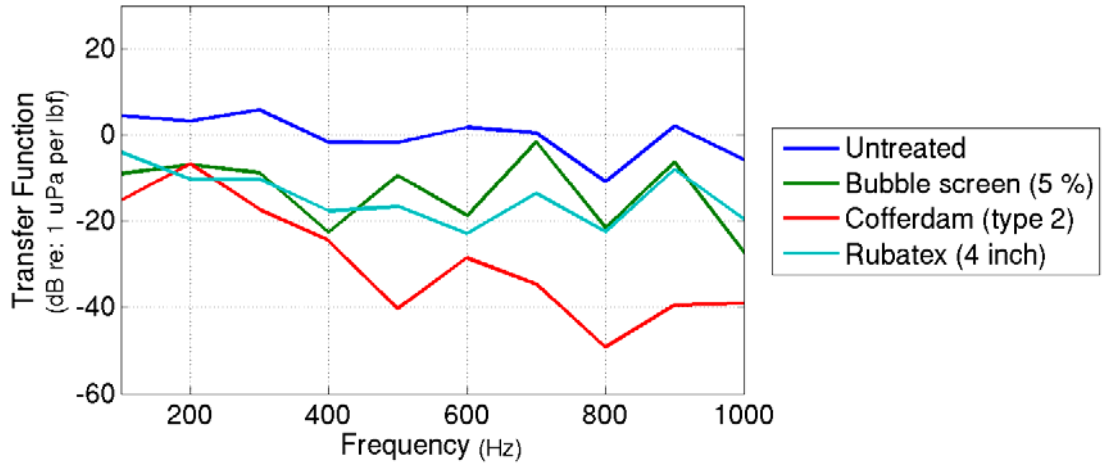
Depth-Averaged Transfer Function versus Frequency (100 m range)

pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 0 m



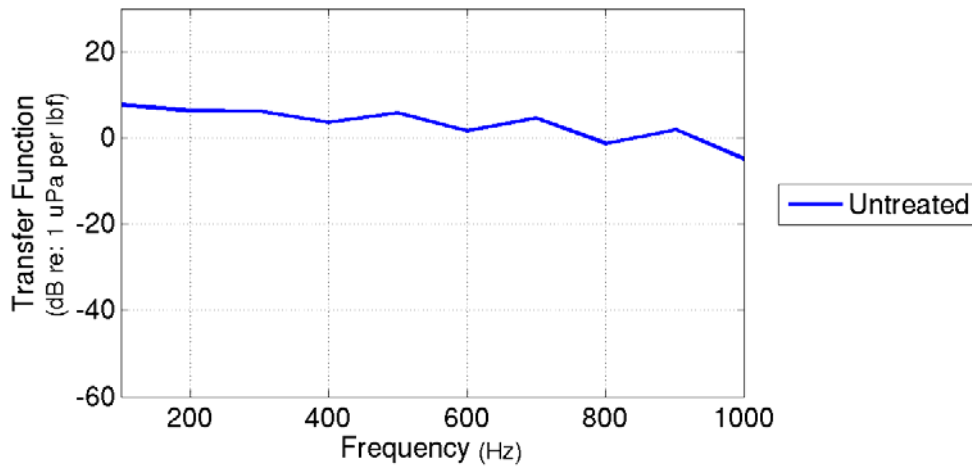
Depth-Averaged Transfer Function versus Frequency (100 m range)

pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



Depth-Averaged Transfer Function versus Frequency (100 m range)

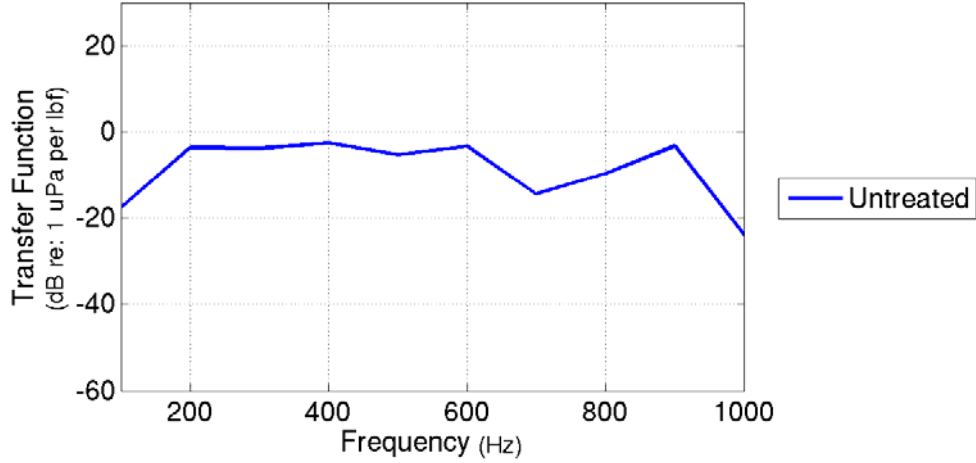
pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 35 m



300 meter range from pile:

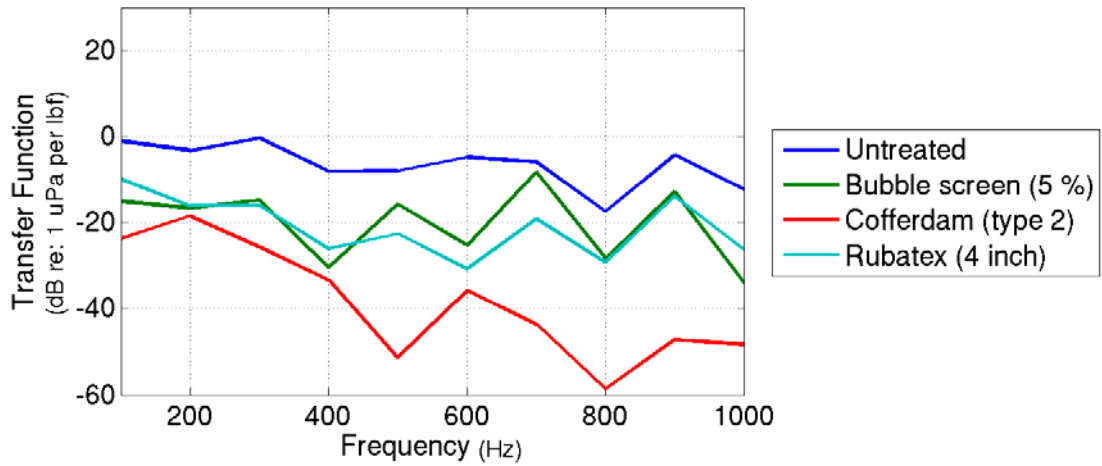
Depth-Averaged Transfer Function versus Frequency (300 m range)

pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 0 m



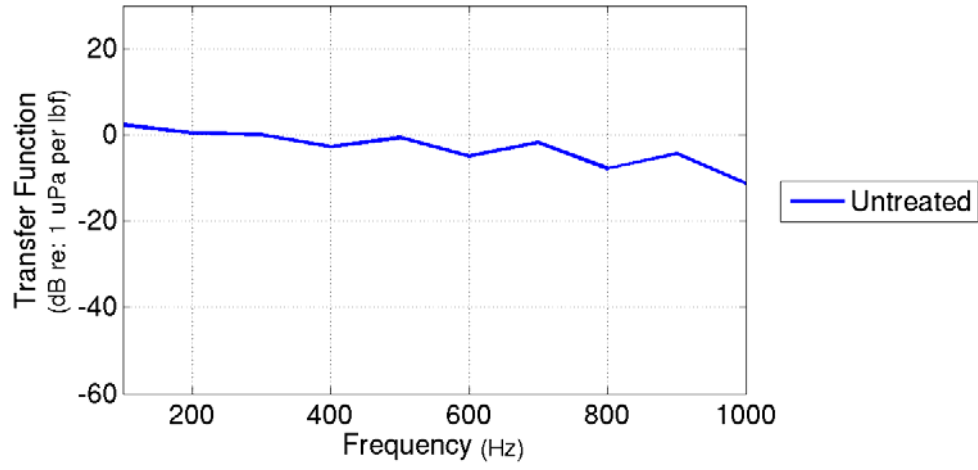
Depth-Averaged Transfer Function versus Frequency (300 m range)

pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



Depth-Averaged Transfer Function versus Frequency (300 m range)

pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 35 m



D. Depth Averaged Transfer Function as a Function of Range

The following figures provide transfer function, averaged over depth, at frequencies of 100 Hz, 200 Hz, 400 Hz, and 800 Hz, as a function of range from the pile. These results provide insight into the effects of propagation through the ocean, enabling comparison of the results of this high fidelity model to the simplistic logarithmic propagation models often used in available pile driving noise studies.

The plots provide results for the pile halfway driven, and contain data for the all treatments considered.

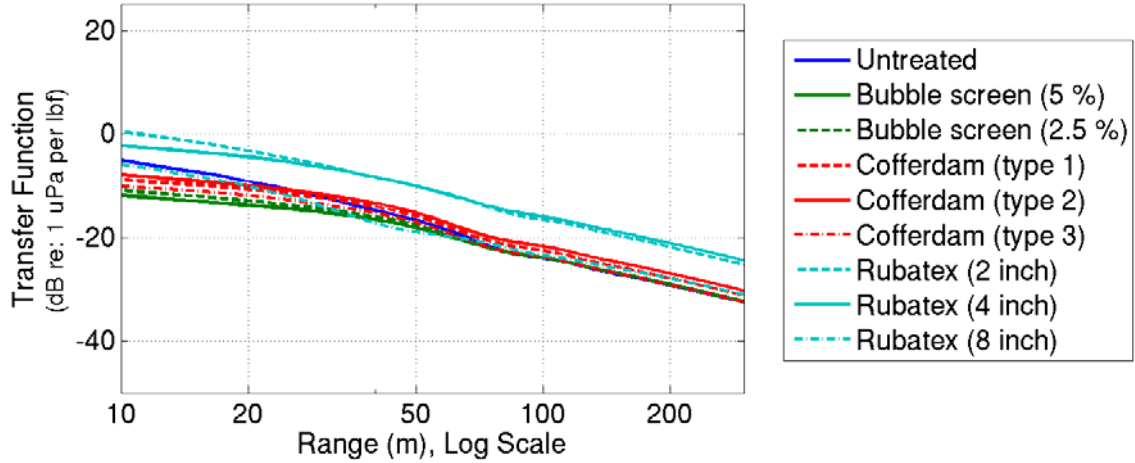
These show the impact of the noise mitigation options, and are consistent with the depth averaged results as a function of range. These plots make it more clear that treatment performance generally increases as frequency increases, which is to be expected. The lowest performance occurs at 100 Hz.

As clearly illustrated in the color plots as a function of depth and range, transmission loss is much more complex than a simple logarithmic function. Some pile driving studies have used propagation loss calculations in the region of $15 * \log(\text{range})$. A rough line fit of the results herein are consistent with this loss calculation, however the fidelity of our results show the large variations in sound that will occur. These variations can have major impacts on marine life and also on measurements conducted to investigate noise events and evaluate treatment effectiveness. Marine life noise mitigation studies and pile driving noise measurement programs must account for the complex nature of underwater sound propagation, especially at the frequencies and ocean depths of interest to pile installations.

15 Meter Ocean Depth

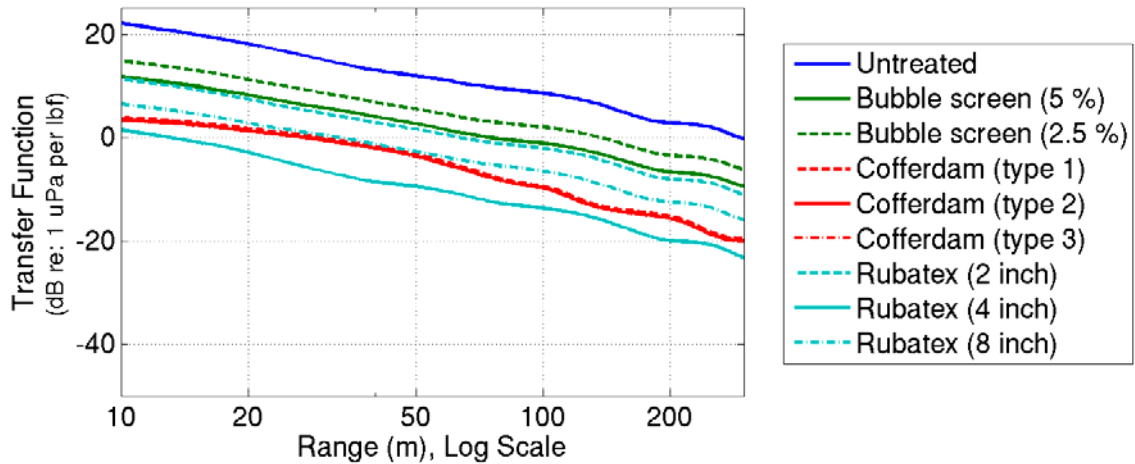
Depth-Averaged Transfer Function versus Range at 100 Hz

pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



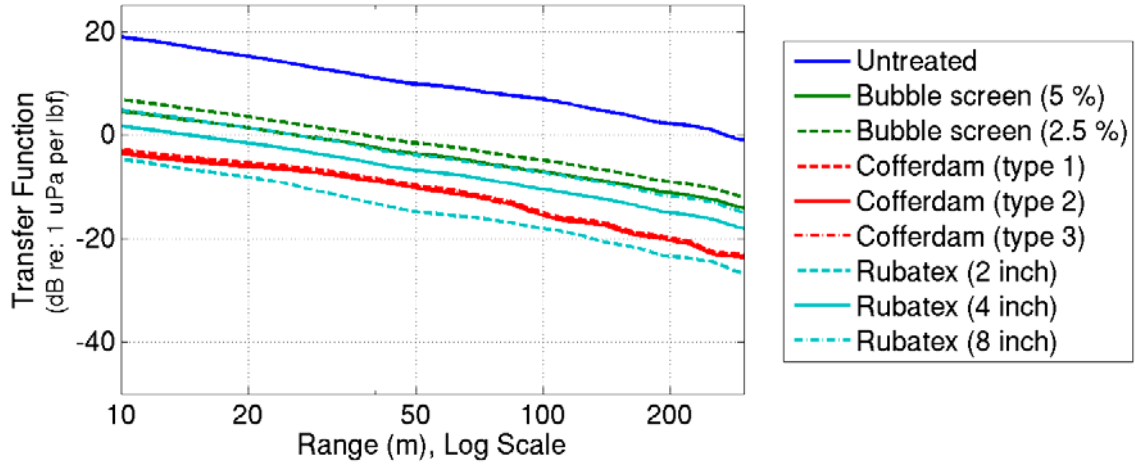
Depth-Averaged Transfer Function versus Range at 200 Hz

pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



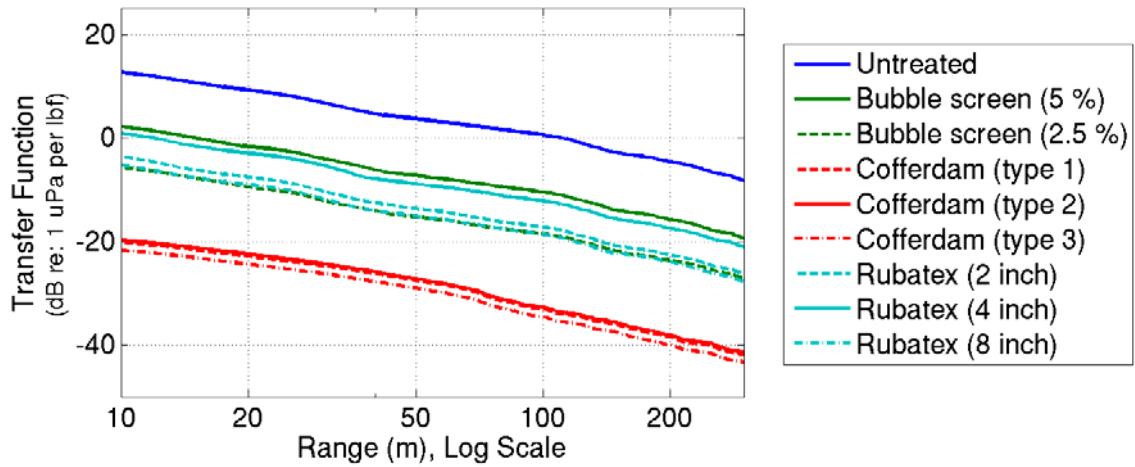
Depth-Averaged Transfer Function versus Range at 400 Hz

pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



Depth-Averaged Transfer Function versus Range at 800 Hz

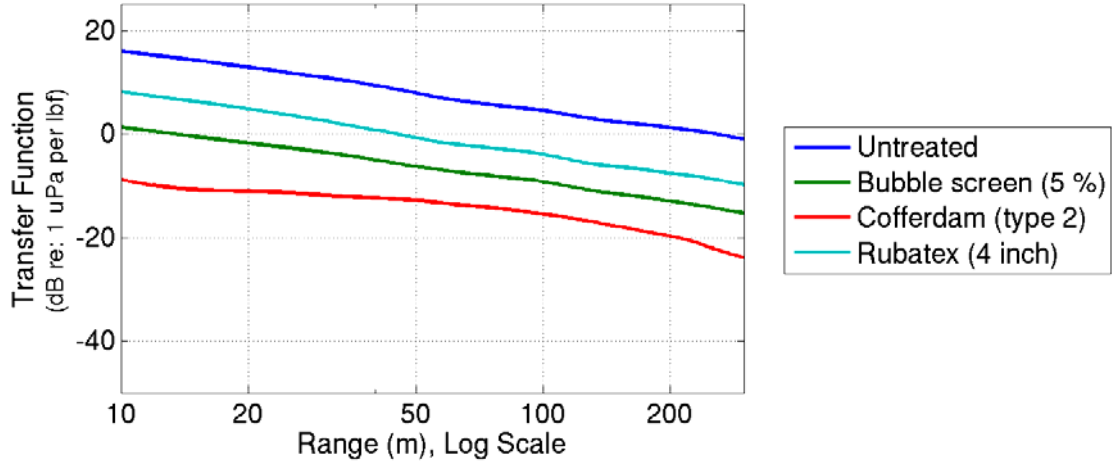
pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



30 Meter Ocean Depth

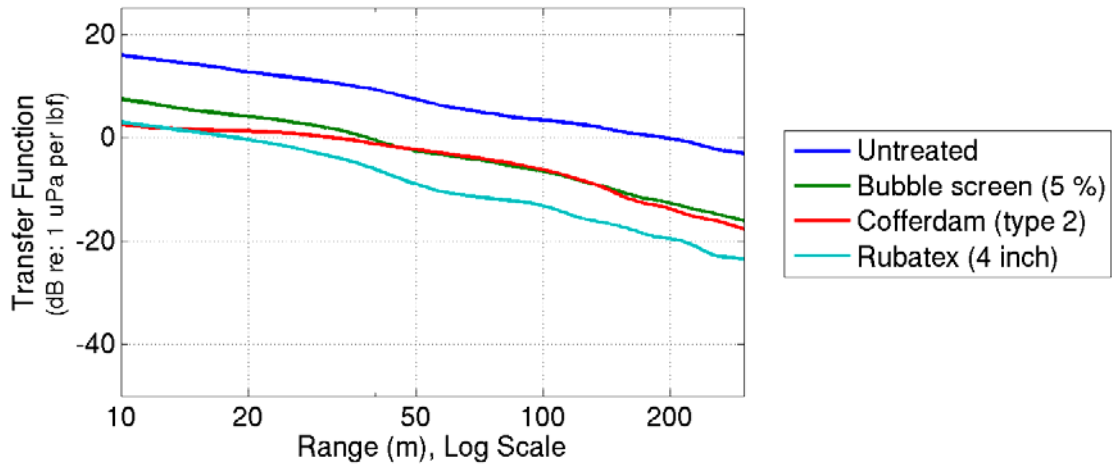
Depth-Averaged Transfer Function versus Range at 100 Hz

pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



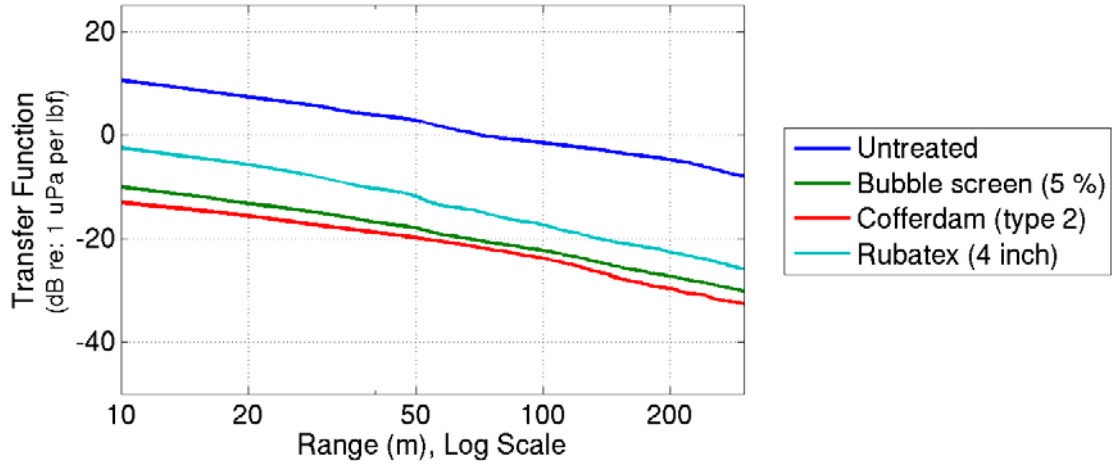
Depth-Averaged Transfer Function versus Range at 200 Hz

pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



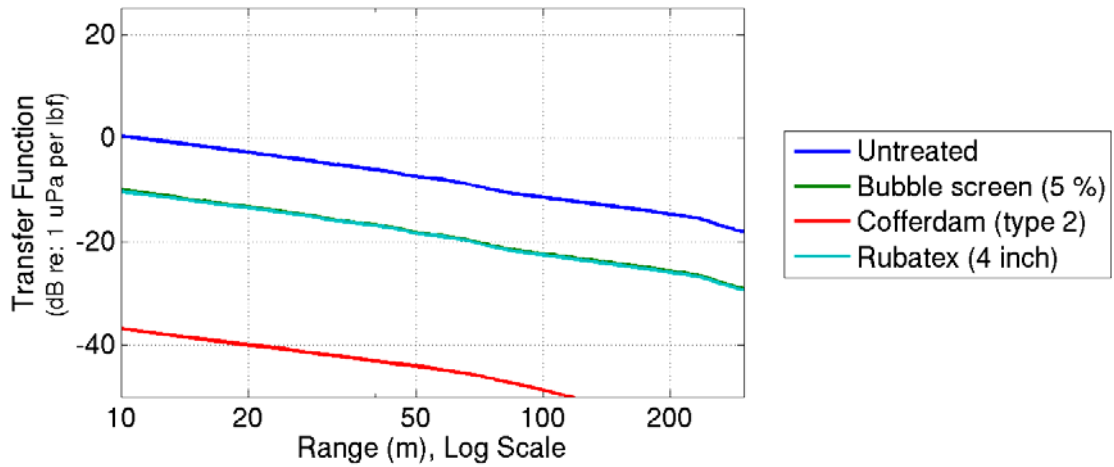
Depth-Averaged Transfer Function versus Range at 400 Hz

pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



Depth-Averaged Transfer Function versus Range at 800 Hz

pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



E. Comparison of Path Contributions

The following figures provide transfer function, averaged over depth, at ranges of 10m, 100m, and 300m from the pile, as a function of frequency. On each plot, the overall transfer function is provided, along with each of the three component paths. These results enable an assessment of the relative contribution of each path, which drives the design of noise mitigation treatments and limiting performance curves.

The plots provide results for the pile at initial contact with the bottom, halfway driven, and fully driven, to illustrate the impact of driven depth. For the 15m water depth cases, the halfway driven plots contain data for the all treatments considered. The 15m plots for initial contact and fully driven shows the transfer function as a function of frequency for the untreated option, 5% bubble screen, and the 4 inch Rubatex. For the 30m water depth cases, the halfway driven plots contain data for the untreated option, 5% bubble screen, the 4 inch Rubatex, and the cofferdam. The 30m plots for initial contact and fully driven shows the transfer function as a function of frequency for the untreated option.

These show the relative contributions of each path, and enable an assessment of their impacts. Findings regarding the transmission paths can be summarized as follows:

1. The structureborne radiation path dominates underwater noise for nearly all cases.
2. The seismic propagation path is not a significant contributor to underwater noise for the untreated case, where the seismic contribution is 10 to 30 dB below the combination of all paths. The seismic contribution is the limiting factor on the overall effectiveness of treating the structureborne radiation path. With bubble screen or compliant layer treatments, the seismic path becomes a contributing or occasionally controlling path at a few frequencies. With a dewatered cofferdam installed (the most effective treatment) the seismic path is the controlling path at most frequencies.
3. The airborne transmission path is not a significant contributor to underwater sound in any case. Even with the cofferdam, the airborne path contribution is 50 dB or more below the combination of all paths.

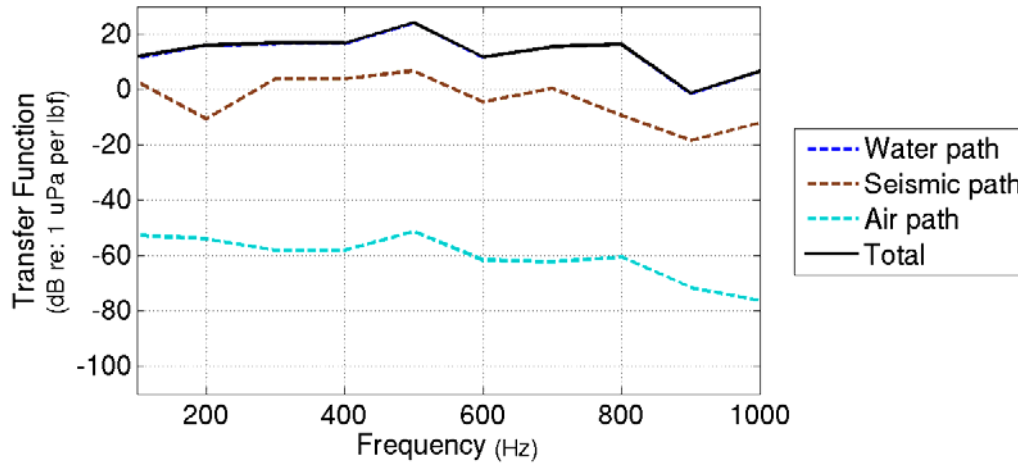
15 Meter Ocean Depth

10 meter range from pile:

First contact with the ocean bottom

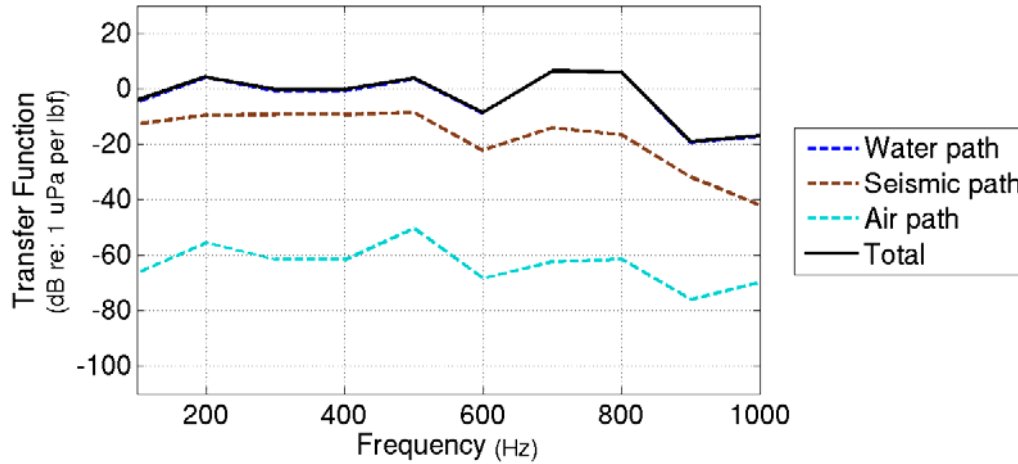
Depth-Averaged Transfer Function Paths versus Frequency (10 m range)

Untreated, pile diameter: 5.5 m, seafloor depth: 15 m, pile penetration into seafloor: 0 m



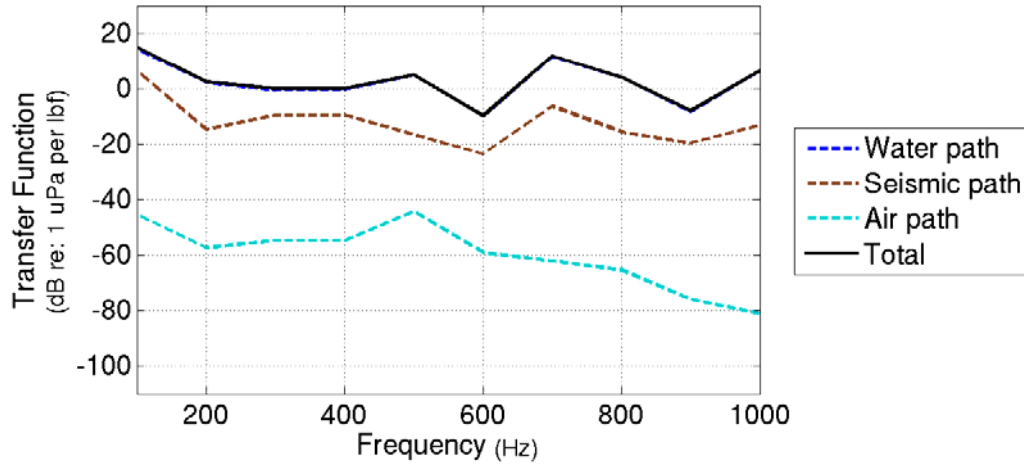
Depth-Averaged Transfer Function Paths versus Frequency (10 m range)

Bubble screen (5 %), pile diameter: 5.5 m, seafloor depth: 15 m, pile penetration into seafloor: 0 m



Depth-Averaged Transfer Function Paths versus Frequency (10 m range)

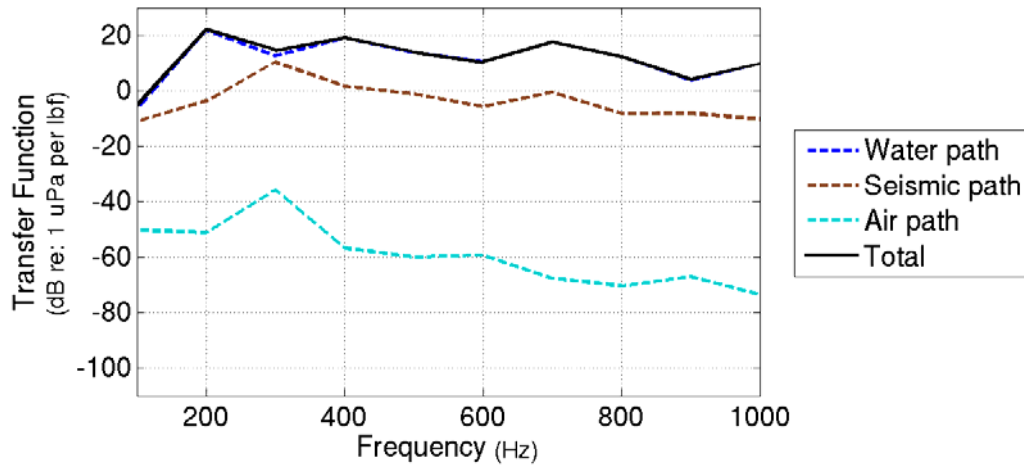
Rubatex (4 inch), pile diameter: 5.5 m, seafloor depth: 15 m, pile penetration into seafloor: 0 m



Halfway driven

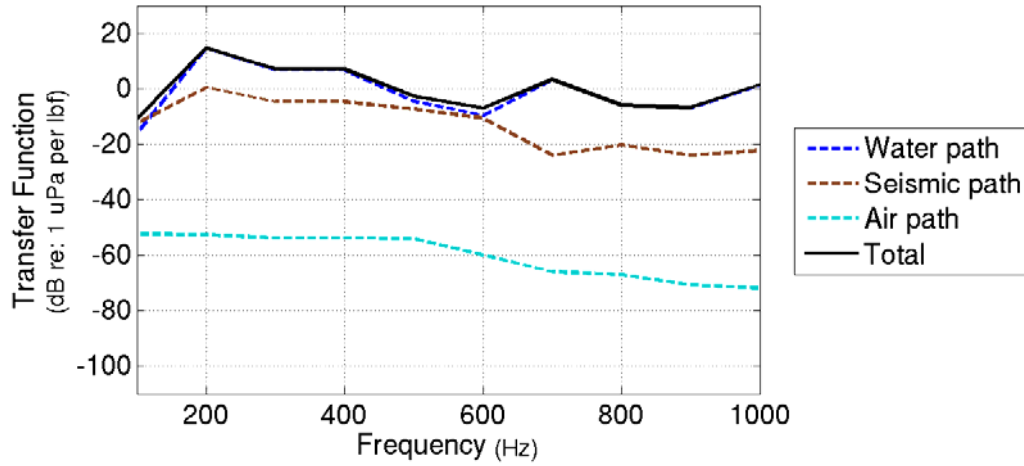
Depth-Averaged Transfer Function Paths versus Frequency (10 m range)

Untreated, pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



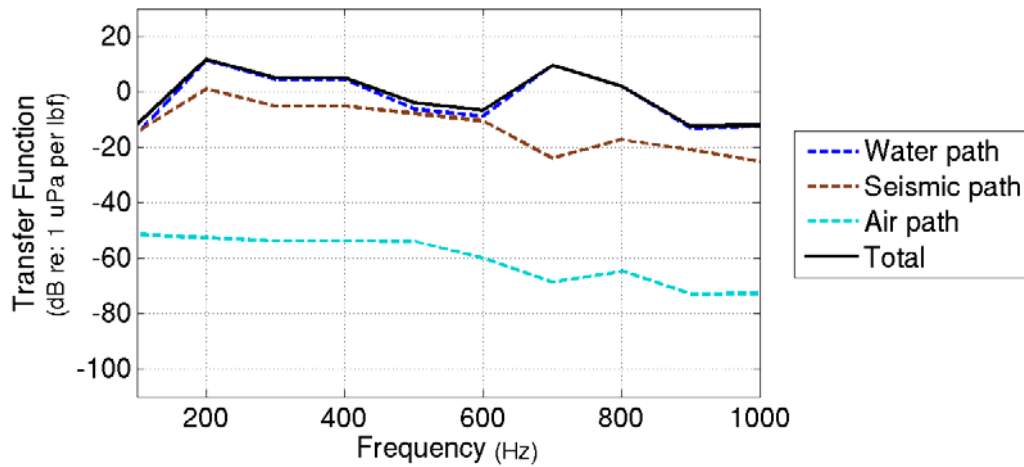
Depth-Averaged Transfer Function Paths versus Frequency (10 m range)

Bubble screen (2.5 %), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



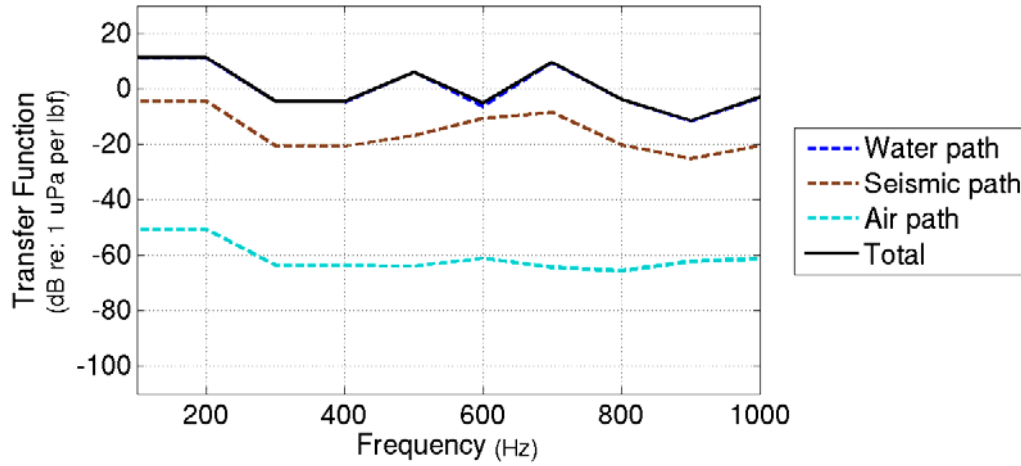
Depth-Averaged Transfer Function Paths versus Frequency (10 m range)

Bubble screen (5 %), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



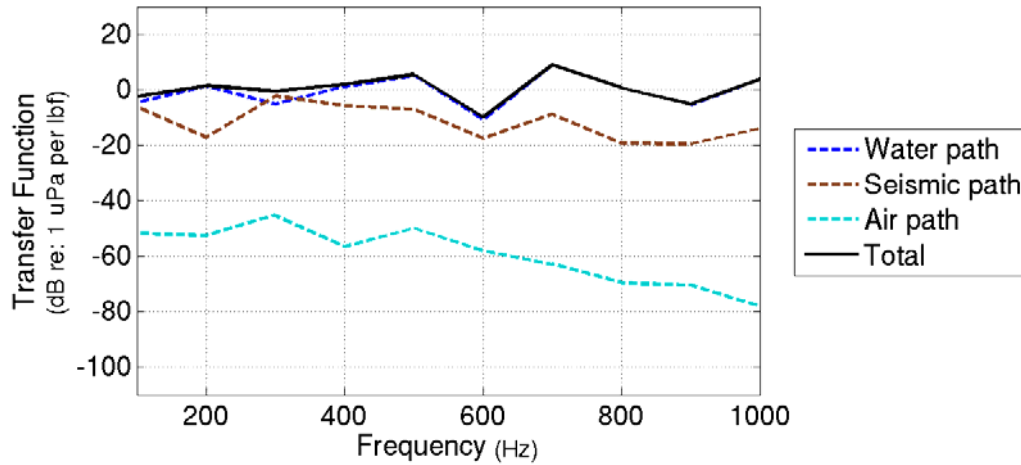
Depth-Averaged Transfer Function Paths versus Frequency (10 m range)

Rubatex (2 inch), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



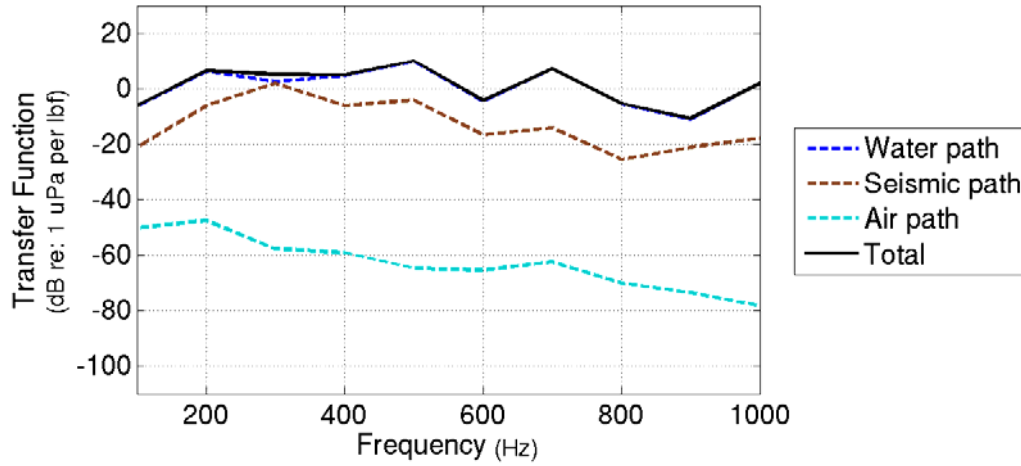
Depth-Averaged Transfer Function Paths versus Frequency (10 m range)

Rubatex (4 inch), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



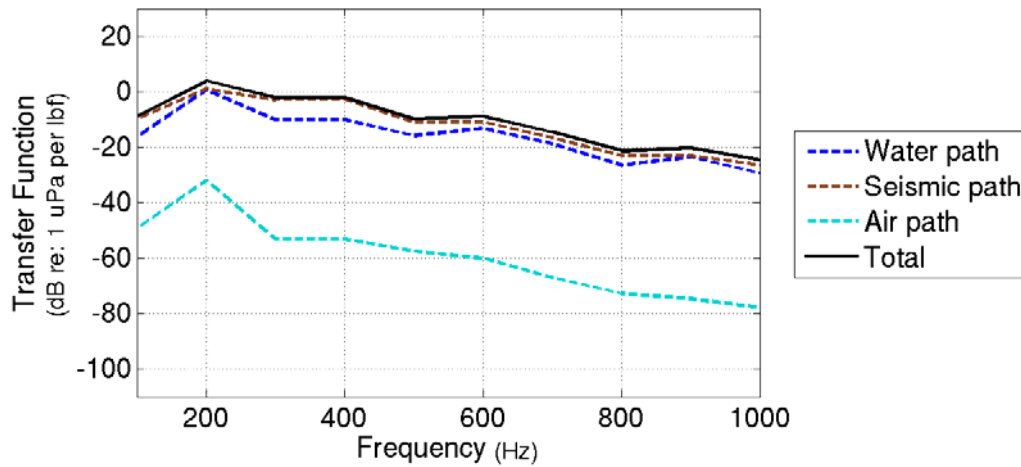
Depth-Averaged Transfer Function Paths versus Frequency (10 m range)

Rubatex (8 inch), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



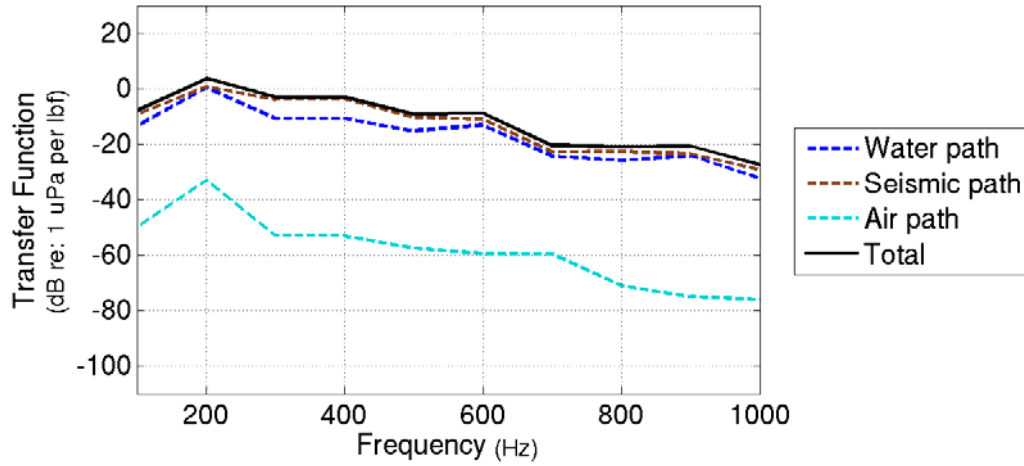
Depth-Averaged Transfer Function Paths versus Frequency (10 m range)

Cofferdam (type 1), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



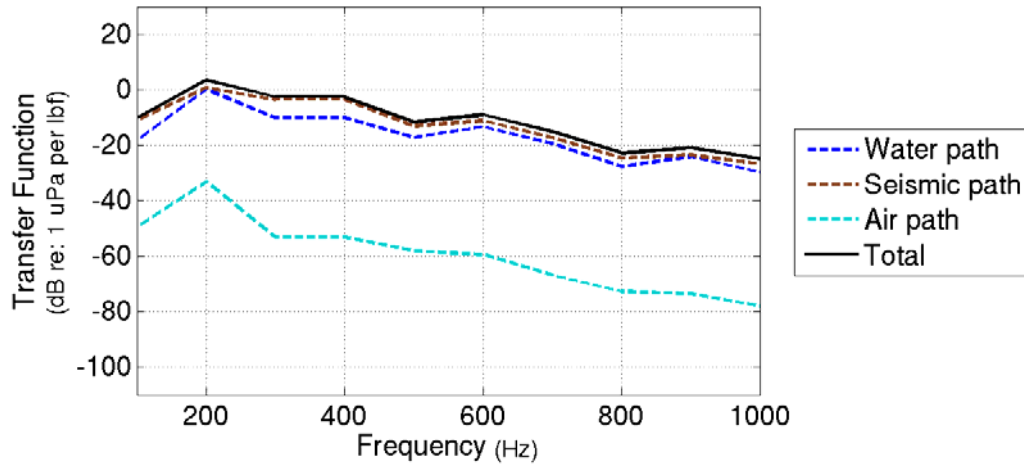
Depth-Averaged Transfer Function Paths versus Frequency (10 m range)

Cofferdam (type 2), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



Depth-Averaged Transfer Function Paths versus Frequency (10 m range)

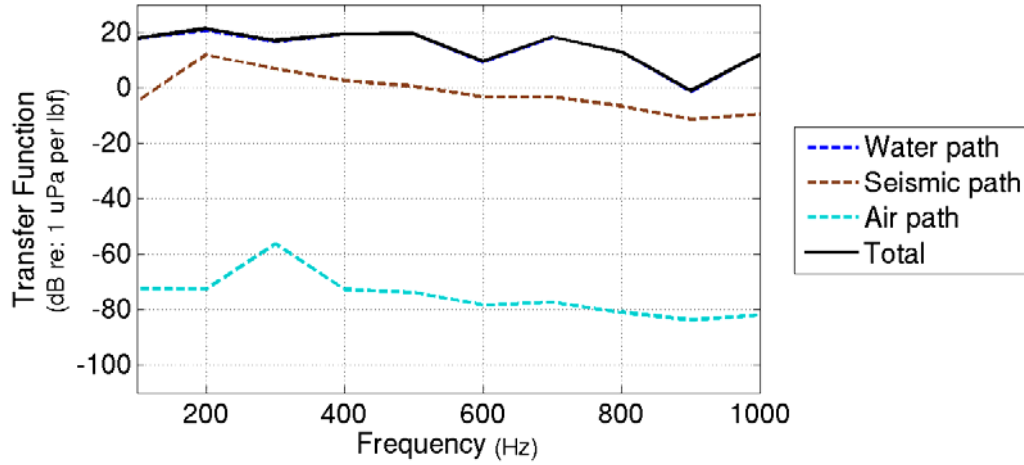
Cofferdam (type 3), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



Fully driven

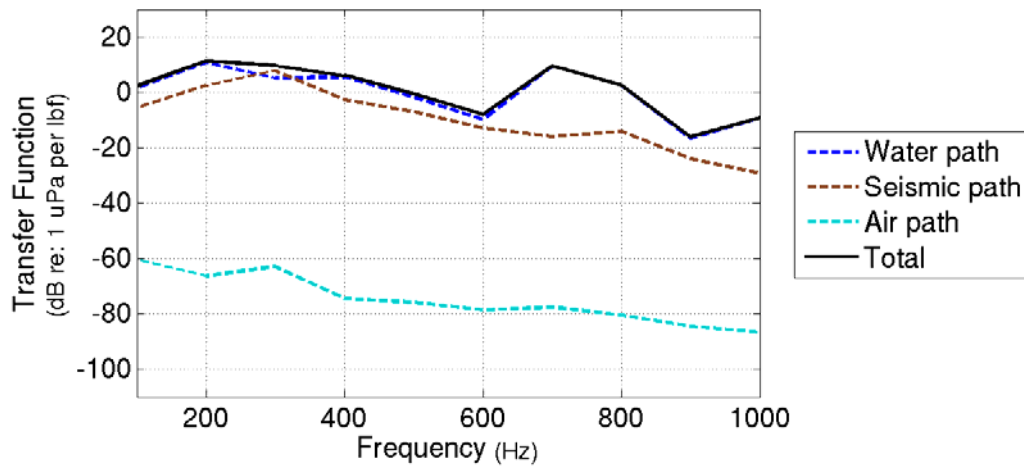
Depth-Averaged Transfer Function Paths versus Frequency (10 m range)

Untreated, pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 26 m



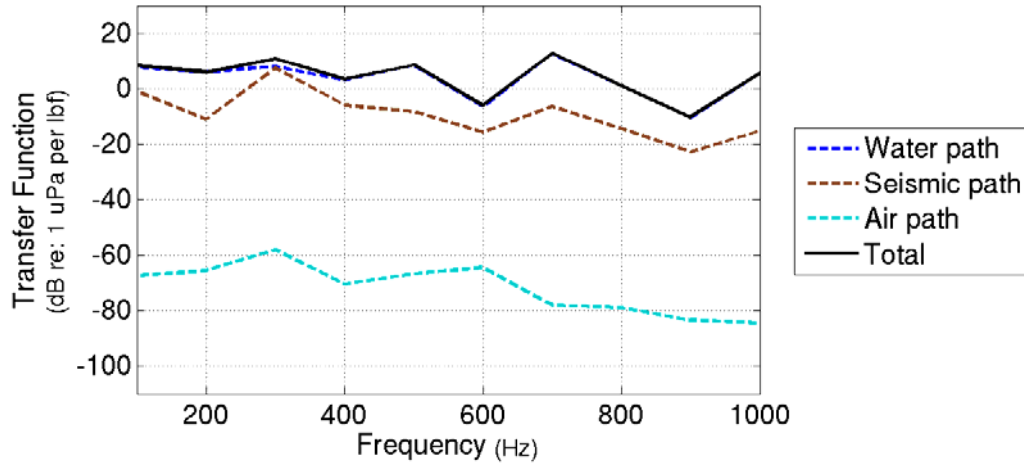
Depth-Averaged Transfer Function Paths versus Frequency (10 m range)

Bubble screen (5 %), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 26 m



Depth-Averaged Transfer Function Paths versus Frequency (10 m range)

Rubatex (4 inch), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 26 m

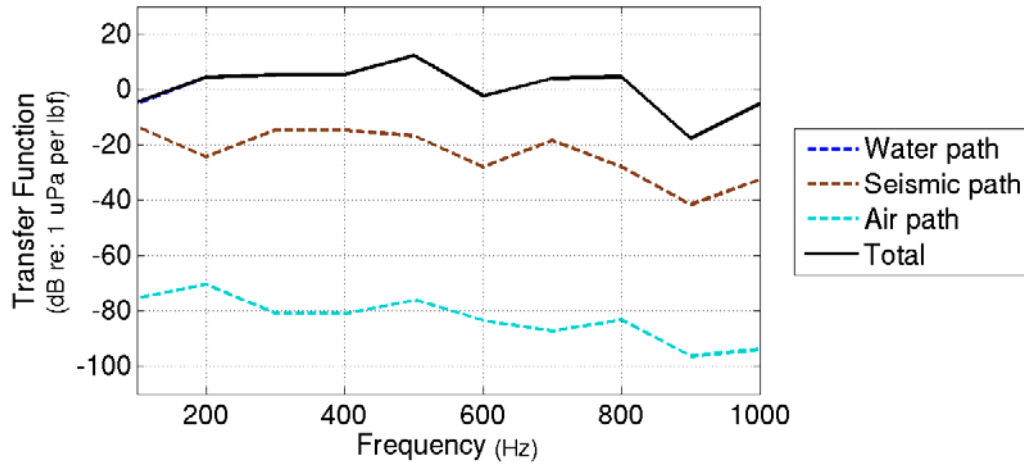


100 meter range from pile:

First contact with the ocean bottom

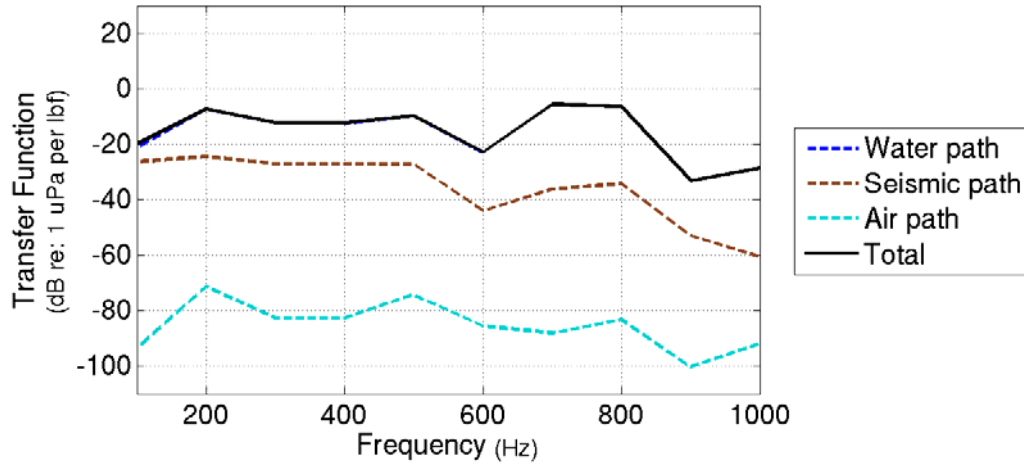
Depth-Averaged Transfer Function Paths versus Frequency (100 m range)

Untreated, pile diameter: 5.5 m, seafloor depth: 15 m, pile penetration into seafloor: 0 m



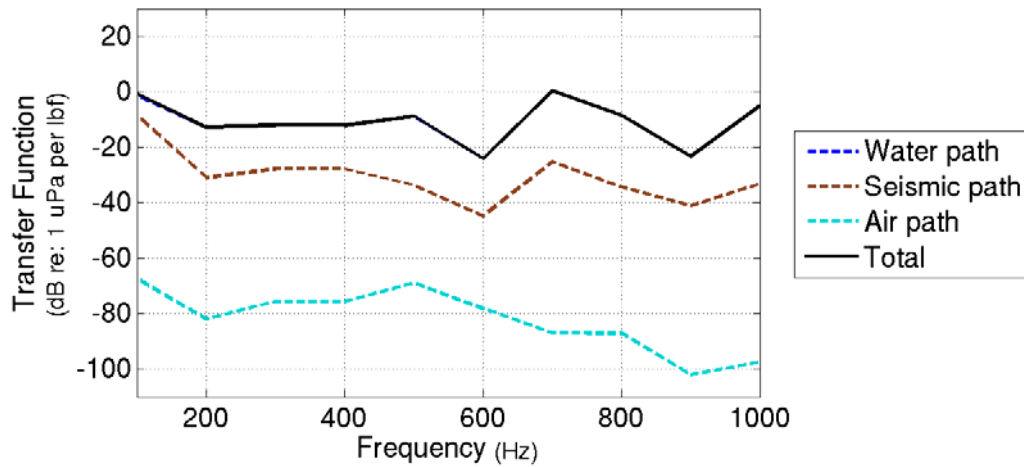
Depth-Averaged Transfer Function Paths versus Frequency (100 m range)

Bubble screen (5%), pile diameter: 5.5 m, seafloor depth: 15 m, pile penetration into seafloor: 0 m



Depth-Averaged Transfer Function Paths versus Frequency (100 m range)

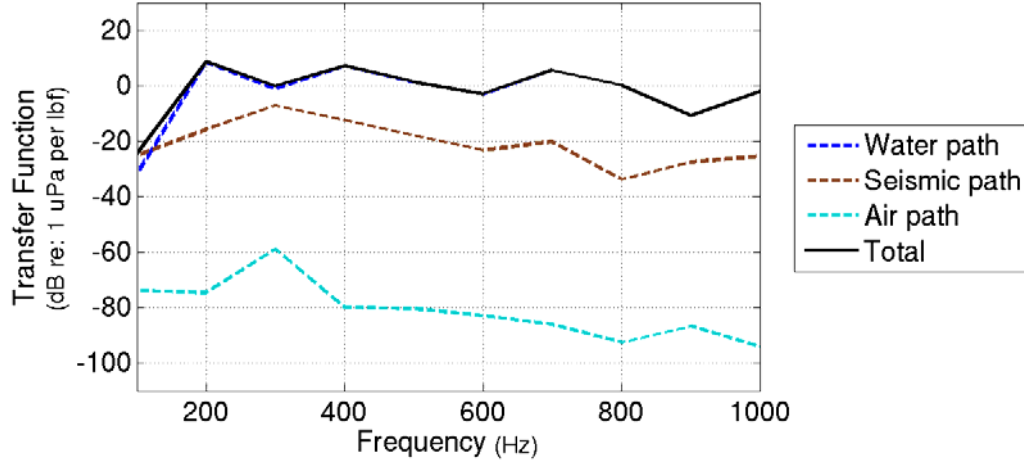
Rubatex (4 inch), pile diameter: 5.5 m, seafloor depth: 15 m, pile penetration into seafloor: 0 m



Halfway driven

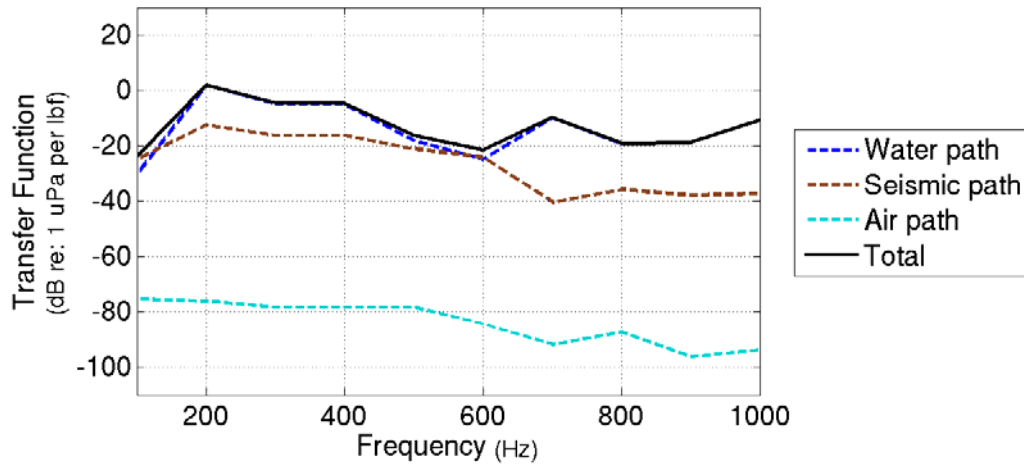
Depth-Averaged Transfer Function Paths versus Frequency (100 m range)

Untreated, pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



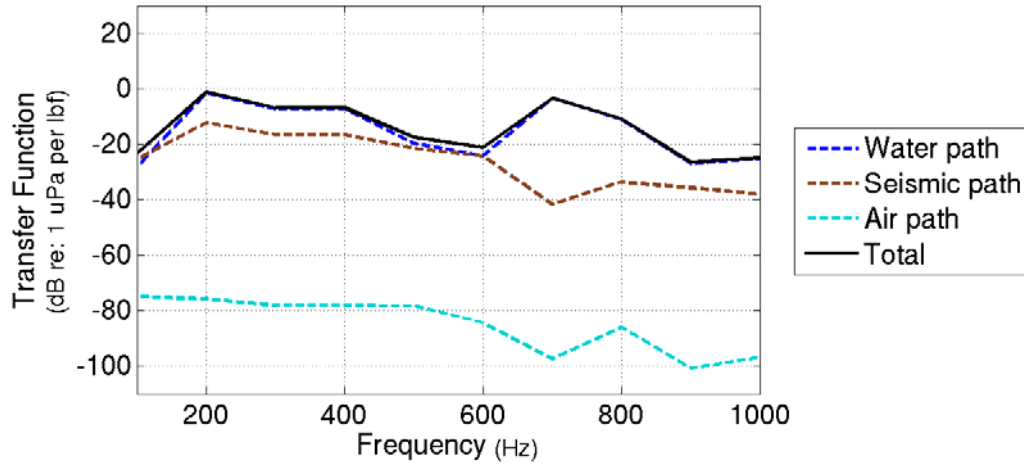
Depth-Averaged Transfer Function Paths versus Frequency (100 m range)

Bubble screen (2.5 %), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



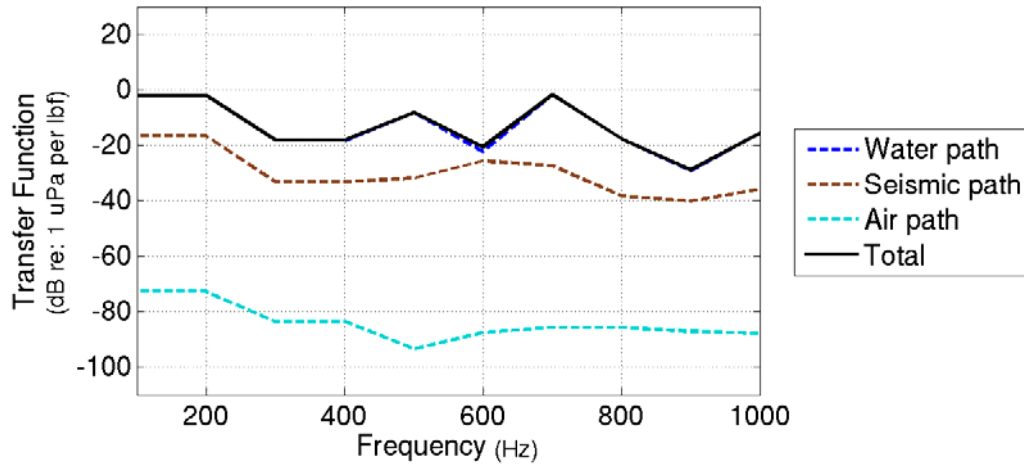
Depth-Averaged Transfer Function Paths versus Frequency (100 m range)

Bubble screen (5 %), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



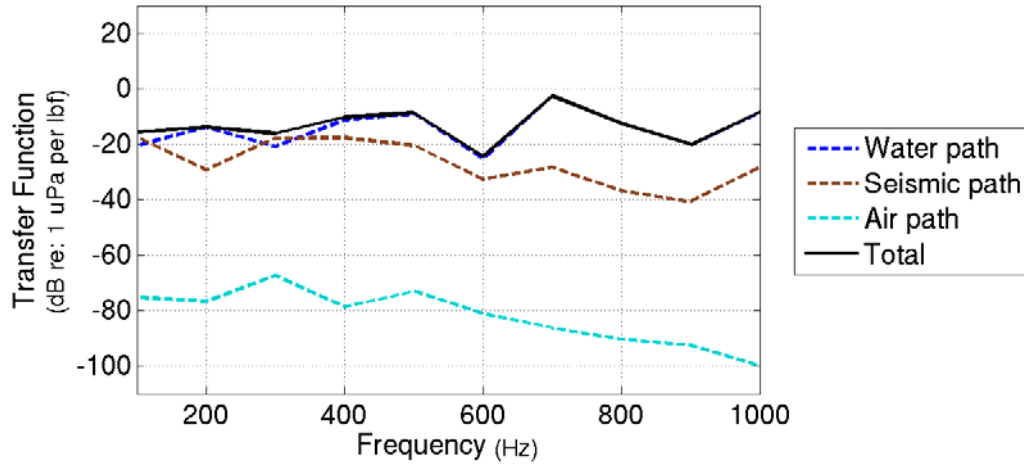
Depth-Averaged Transfer Function Paths versus Frequency (100 m range)

Rubatex (2 inch), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



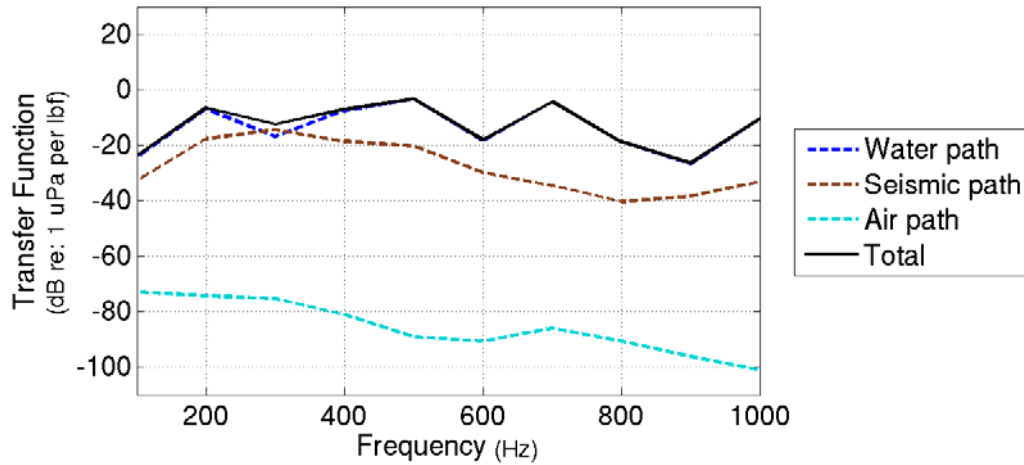
Depth-Averaged Transfer Function Paths versus Frequency (100 m range)

Rubatex (4 inch), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



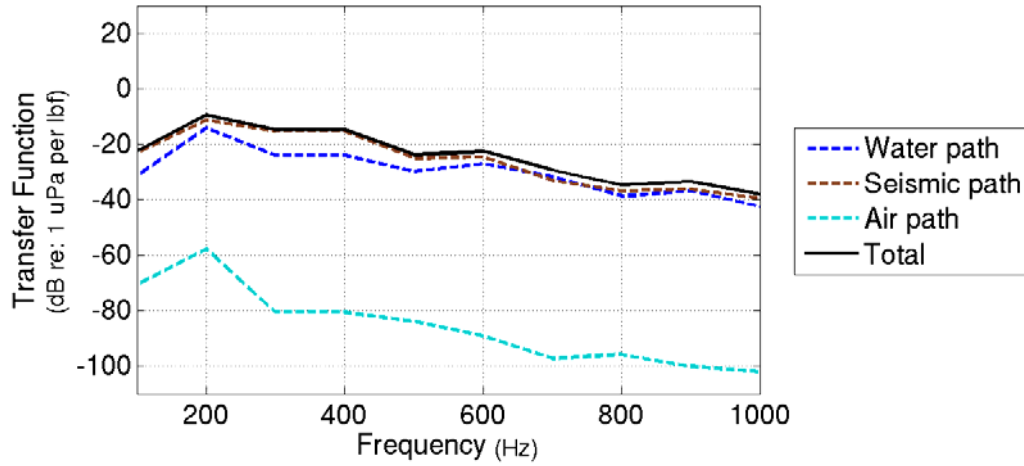
Depth-Averaged Transfer Function Paths versus Frequency (100 m range)

Rubatex (8 inch), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



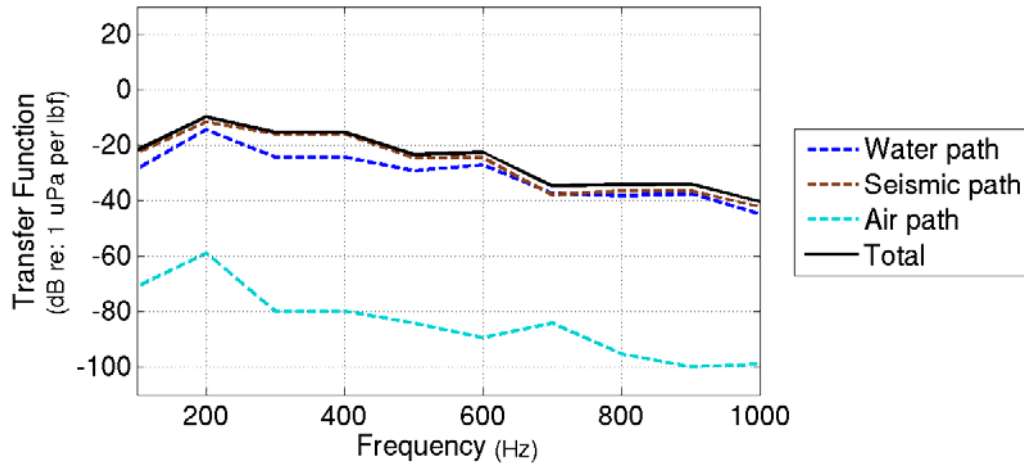
Depth-Averaged Transfer Function Paths versus Frequency (100 m range)

Cofferdam (type 1), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



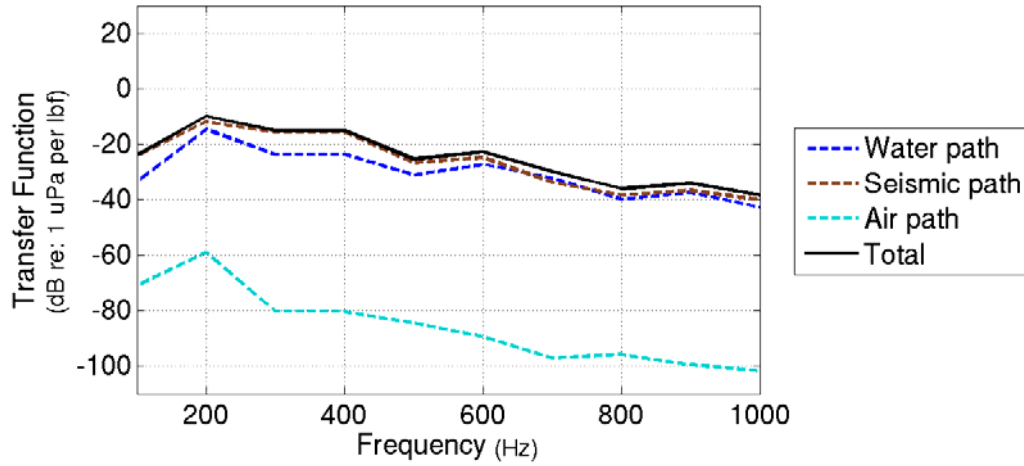
Depth-Averaged Transfer Function Paths versus Frequency (100 m range)

Cofferdam (type 2), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



Depth-Averaged Transfer Function Paths versus Frequency (100 m range)

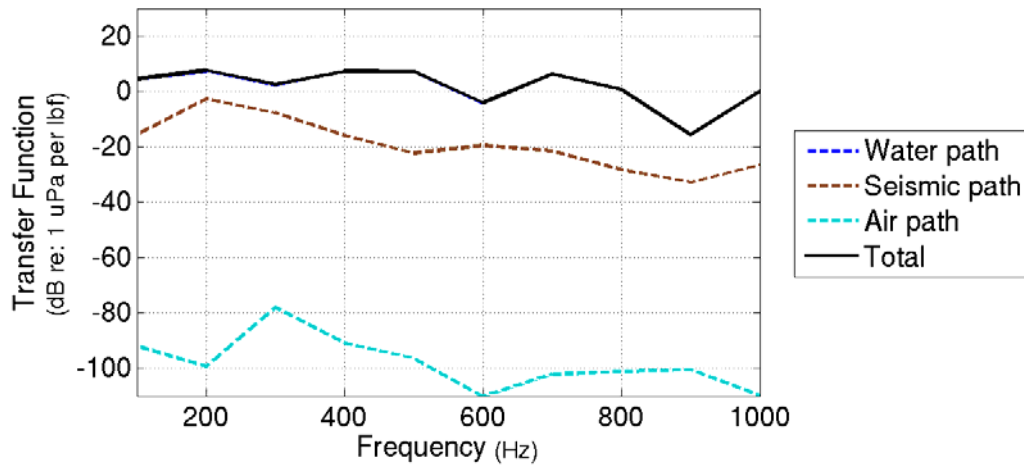
Cofferdam (type 3), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



Fully driven

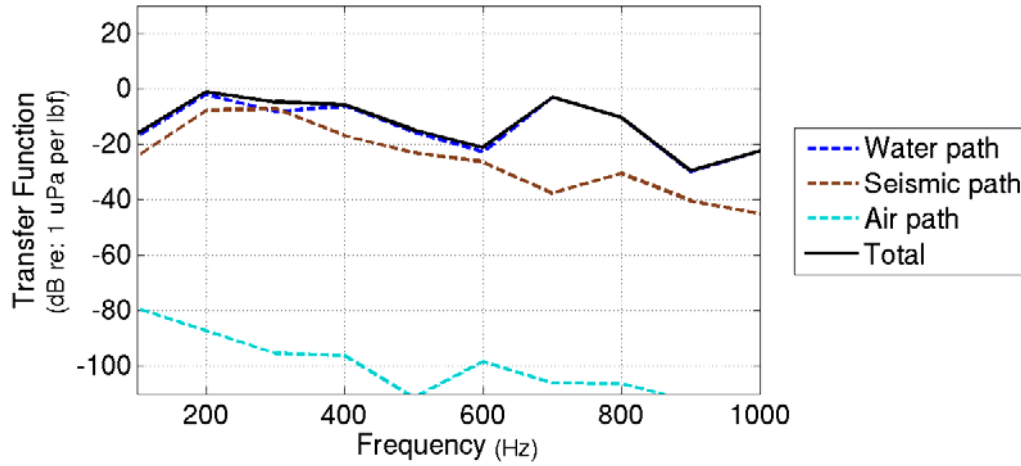
Depth-Averaged Transfer Function Paths versus Frequency (100 m range)

Untreated, pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 26 m



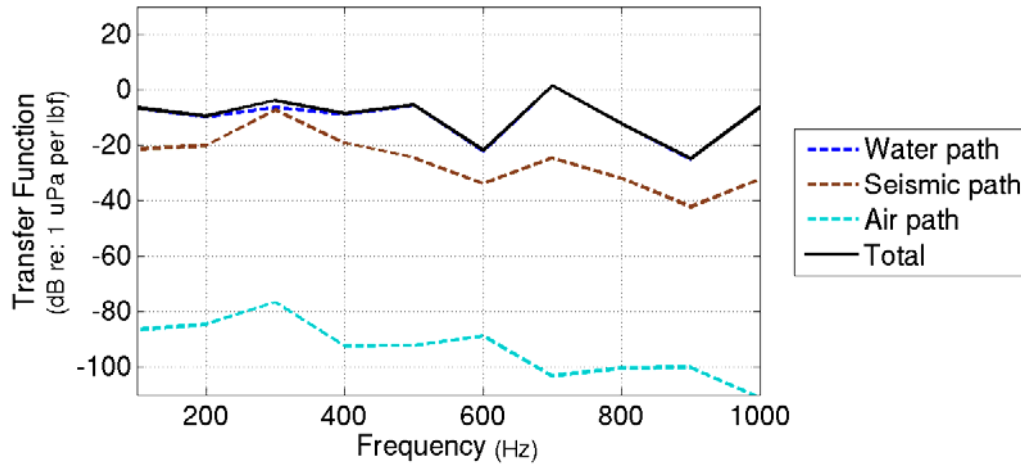
Depth-Averaged Transfer Function Paths versus Frequency (100 m range)

Bubble screen (5 %), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 26 m



Depth-Averaged Transfer Function Paths versus Frequency (100 m range)

Rubatex (4 inch), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 26 m

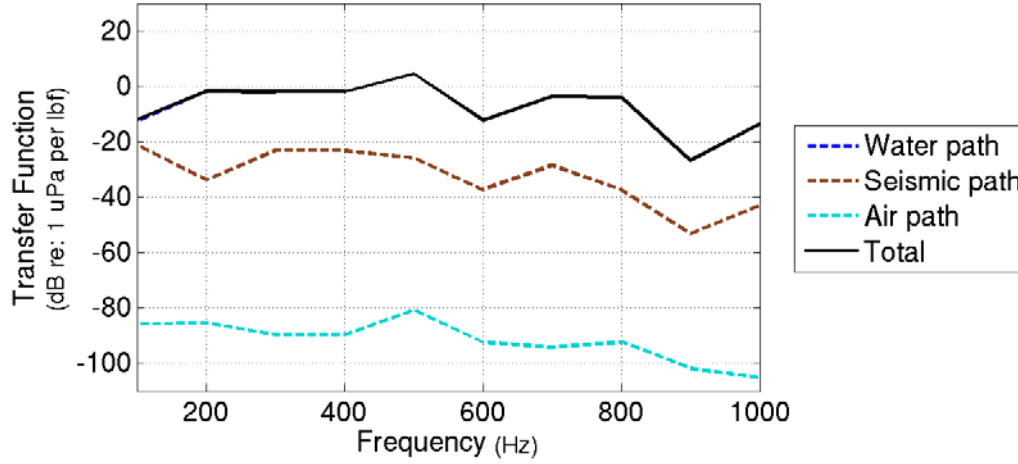


300 meter range from pile:

First contact with the ocean bottom

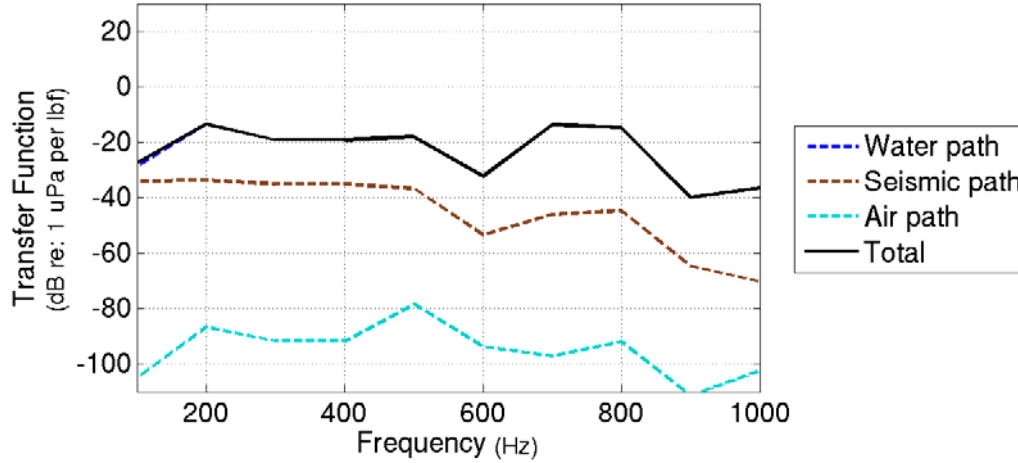
Depth-Averaged Transfer Function Paths versus Frequency (300 m range)

Untreated, pile diameter: 5.5 m, seafloor depth: 15 m, pile penetration into seafloor: 0 m



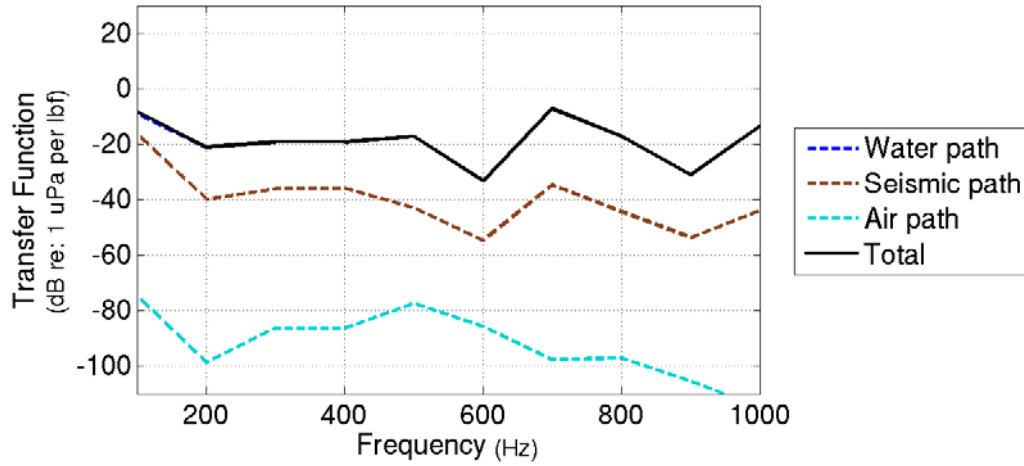
Depth-Averaged Transfer Function Paths versus Frequency (300 m range)

Bubble screen (5 %), pile diameter: 5.5 m, seafloor depth: 15 m, pile penetration into seafloor: 0 m



Depth-Averaged Transfer Function Paths versus Frequency (300 m range)

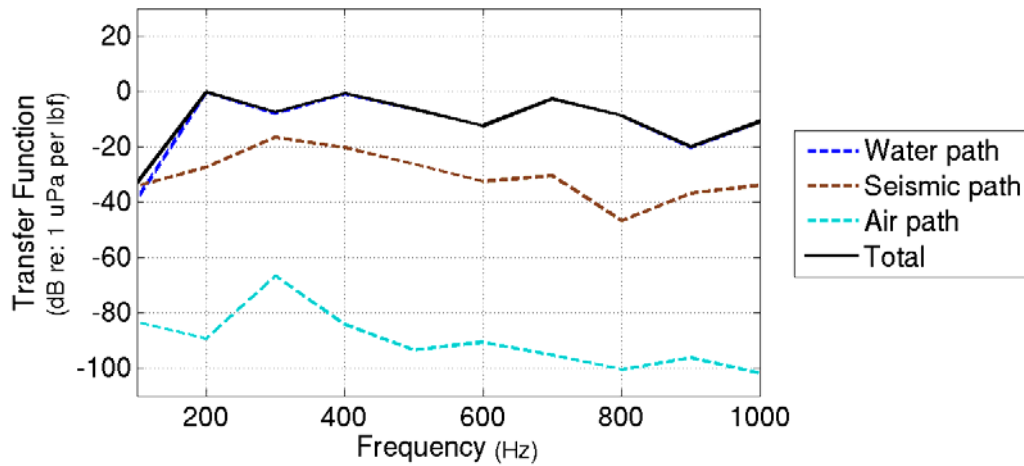
Rubatex (4 inch), pile diameter: 5.5 m, seafloor depth: 15 m, pile penetration into seafloor: 0 m



Halfway driven

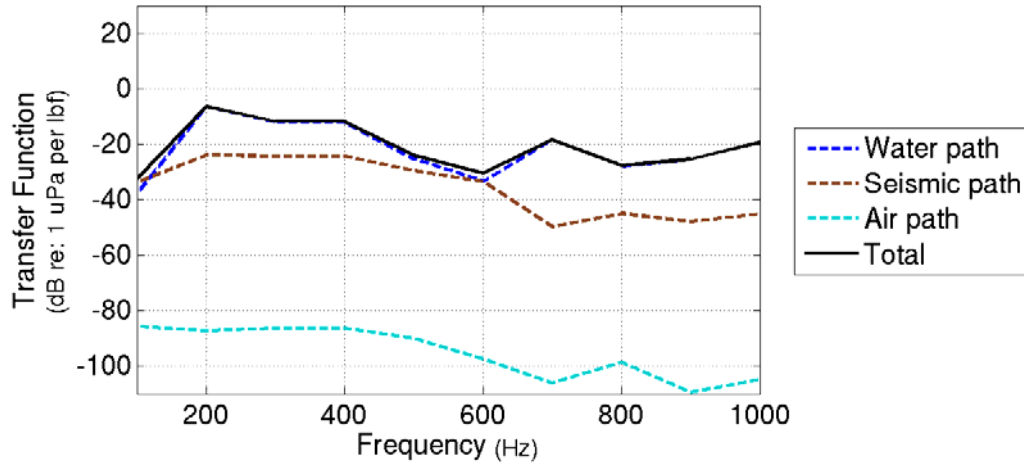
Depth-Averaged Transfer Function Paths versus Frequency (300 m range)

Untreated, pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



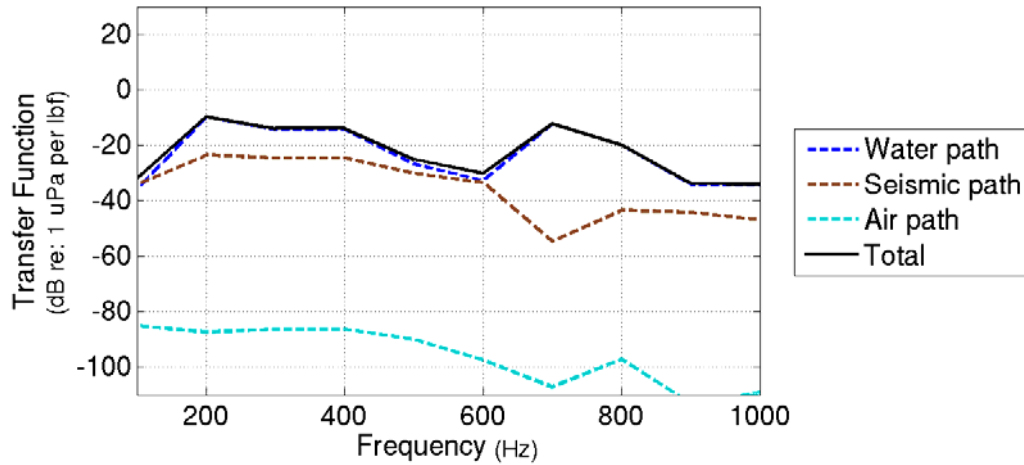
Depth-Averaged Transfer Function Paths versus Frequency (300 m range)

Bubble screen (2.5 %), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



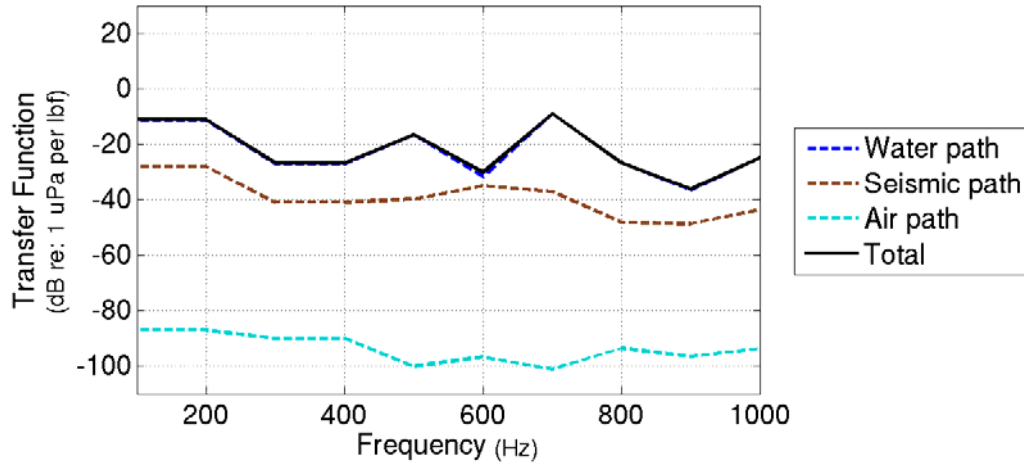
Depth-Averaged Transfer Function Paths versus Frequency (300 m range)

Bubble screen (5 %), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



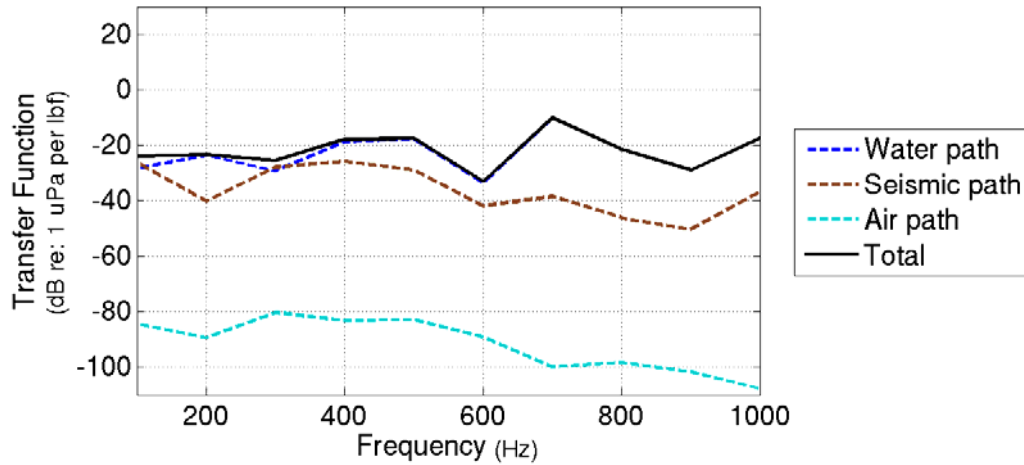
Depth-Averaged Transfer Function Paths versus Frequency (300 m range)

Rubatex (2 inch), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



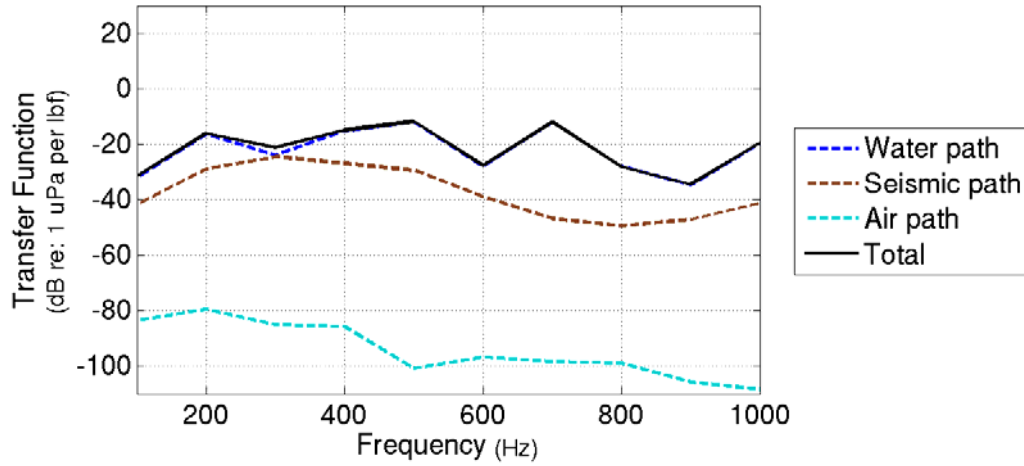
Depth-Averaged Transfer Function Paths versus Frequency (300 m range)

Rubatex (4 inch), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



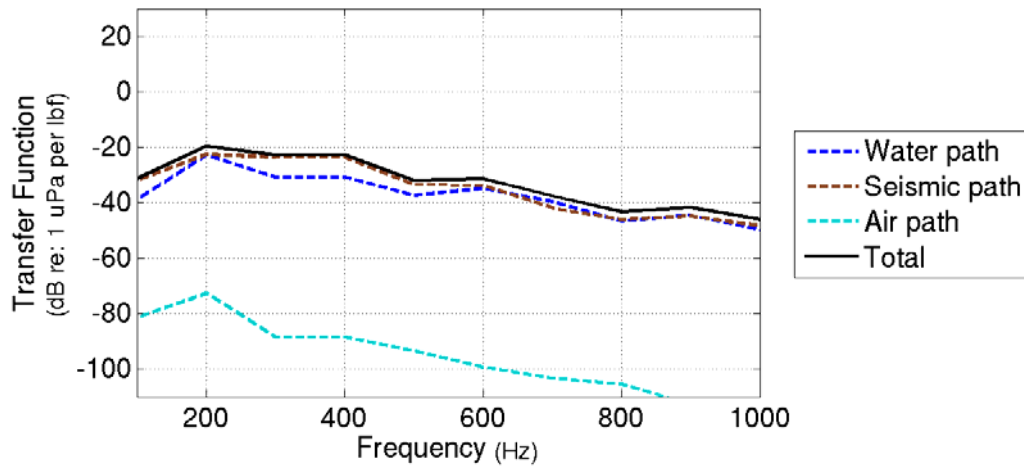
Depth-Averaged Transfer Function Paths versus Frequency (300 m range)

Rubatex (8 inch), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



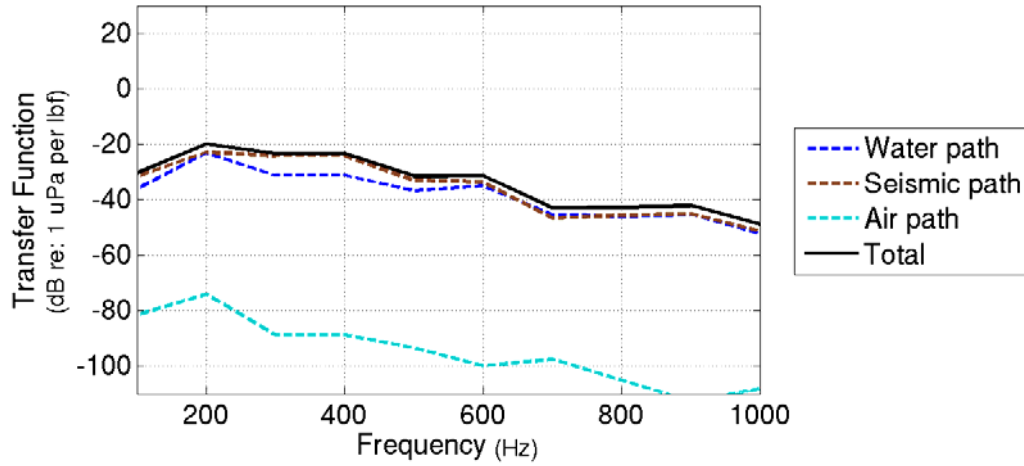
Depth-Averaged Transfer Function Paths versus Frequency (300 m range)

Cofferdam (type 1), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



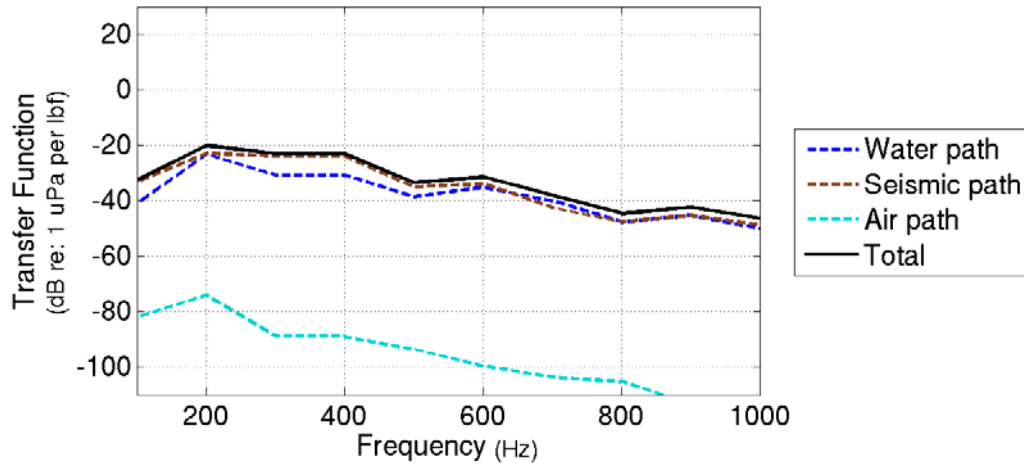
Depth-Averaged Transfer Function Paths versus Frequency (300 m range)

Cofferdam (type 2), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



Depth-Averaged Transfer Function Paths versus Frequency (300 m range)

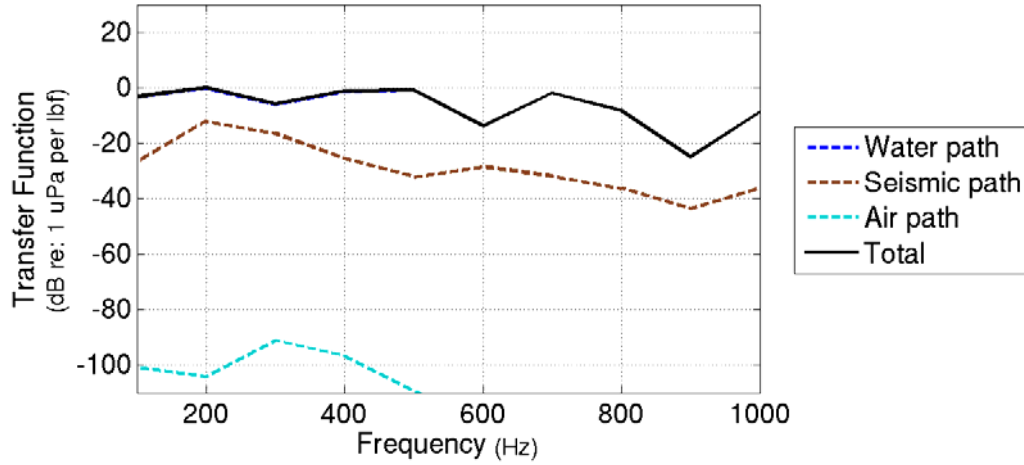
Cofferdam (type 3), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 13 m



Fully driven

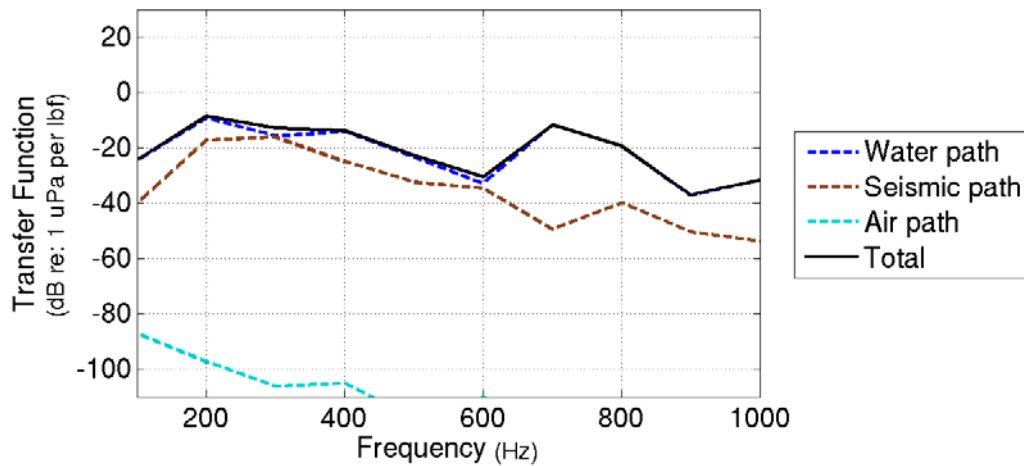
Depth-Averaged Transfer Function Paths versus Frequency (300 m range)

Untreated, pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 26 m



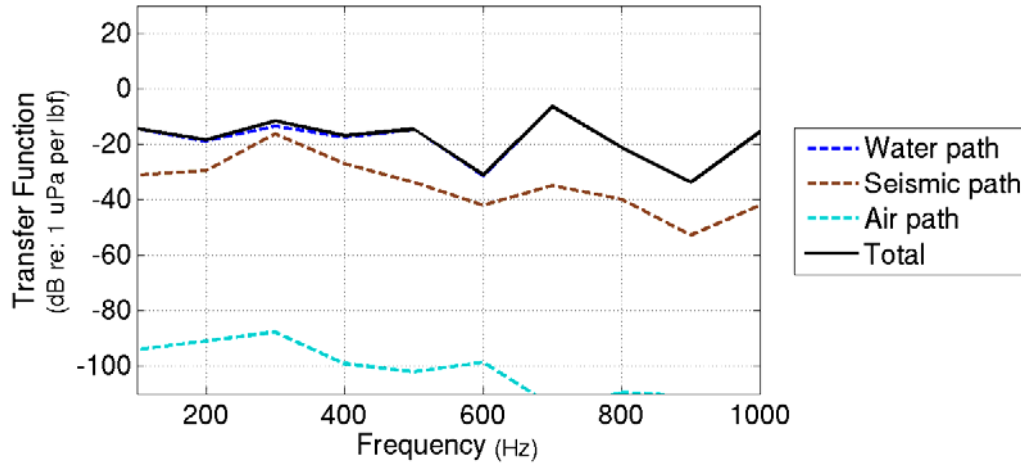
Depth-Averaged Transfer Function Paths versus Frequency (300 m range)

Bubble screen (5 %), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 26 m



Depth-Averaged Transfer Function Paths versus Frequency (300 m range)

Rubatex (4 inch), pile diameter: 5.5m, seafloor depth: 15 m, pile penetration into seafloor: 26 m



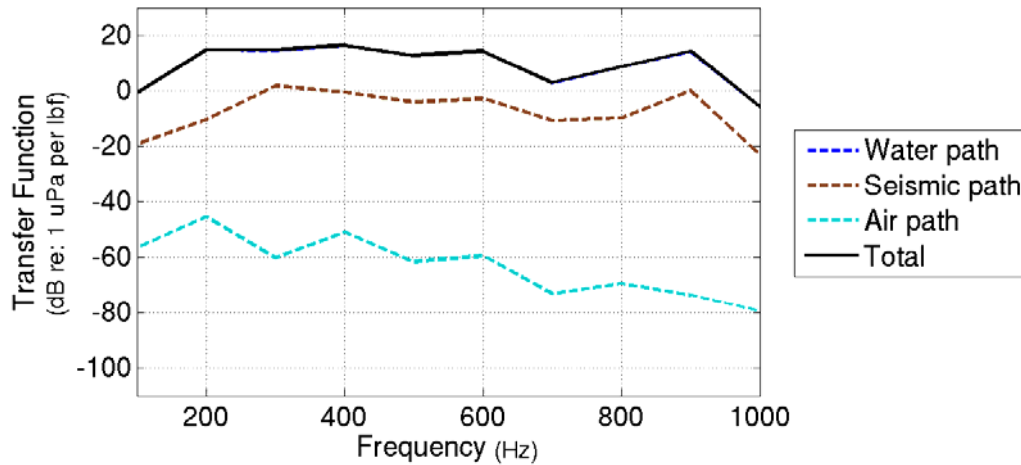
30 Meter Ocean Depth

10 meter range from pile:

First contact with the ocean bottom

Depth-Averaged Transfer Function Paths versus Frequency (10 m range)

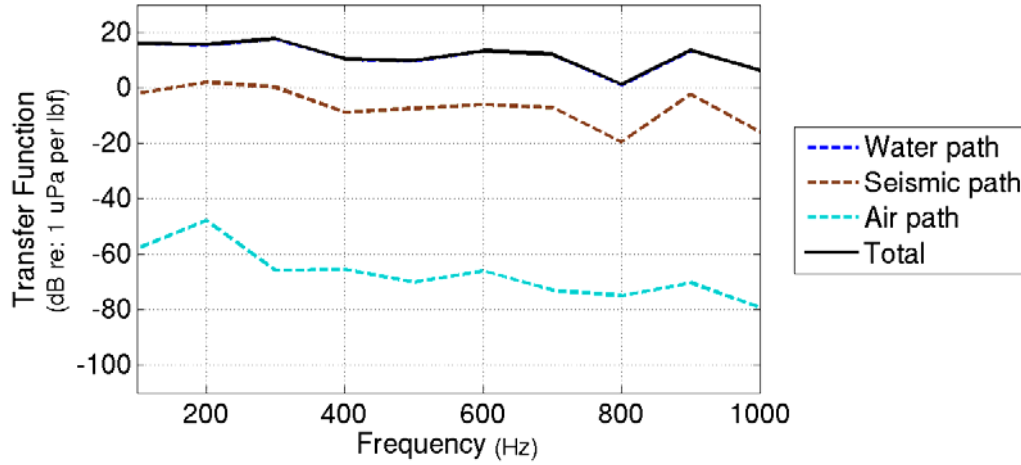
Untreated, pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 0 m



Halfway driven

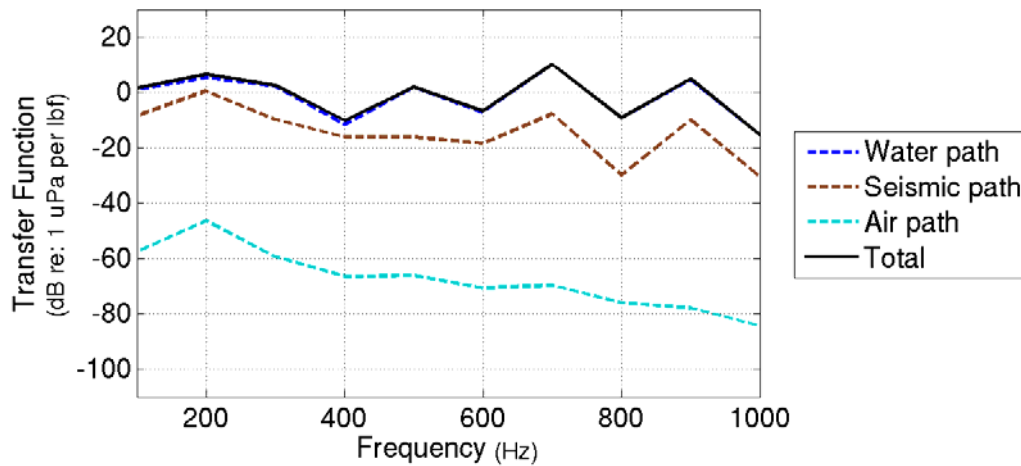
Depth-Averaged Transfer Function Paths versus Frequency (10 m range)

Untreated, pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



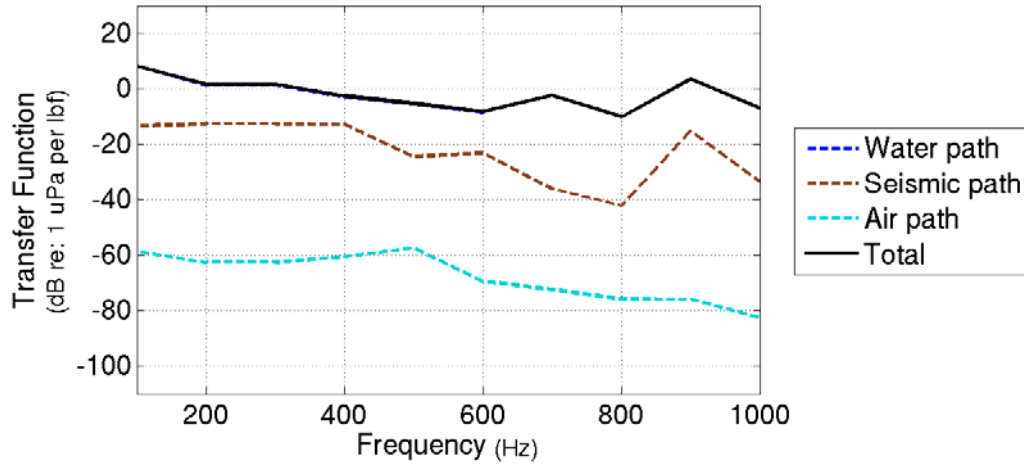
Depth-Averaged Transfer Function Paths versus Frequency (10 m range)

Bubble screen (5 %), pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



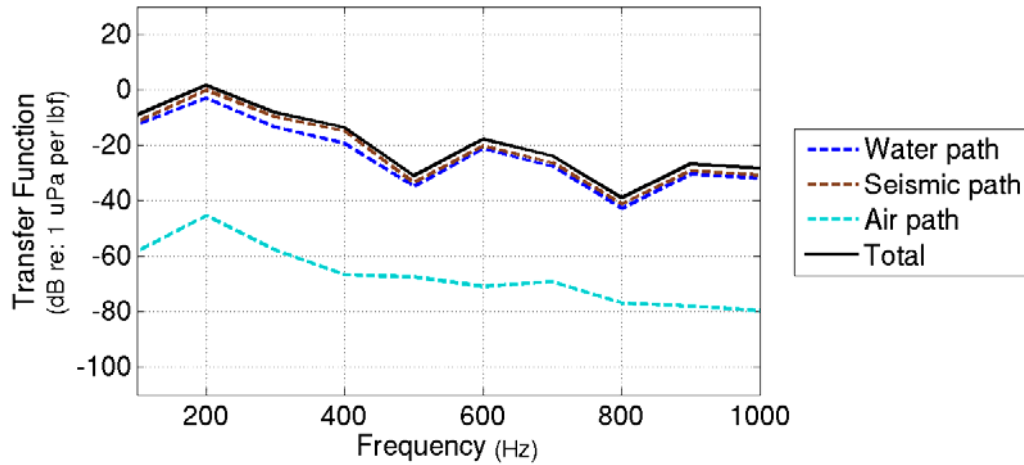
Depth-Averaged Transfer Function Paths versus Frequency (10 m range)

Rubatex (4 inch), pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m

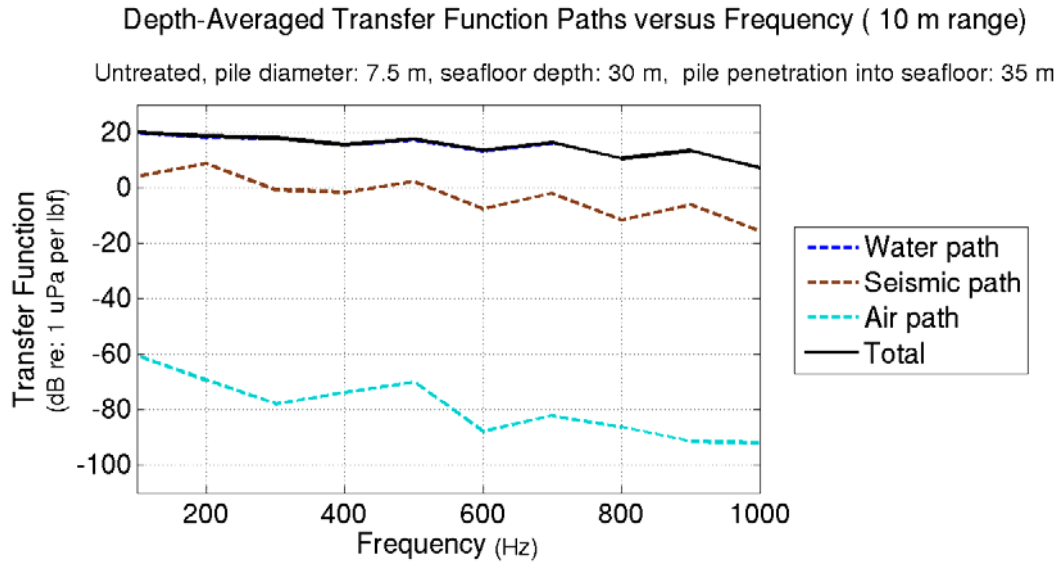


Depth-Averaged Transfer Function Paths versus Frequency (10 m range)

Cofferdam (type 2), pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m

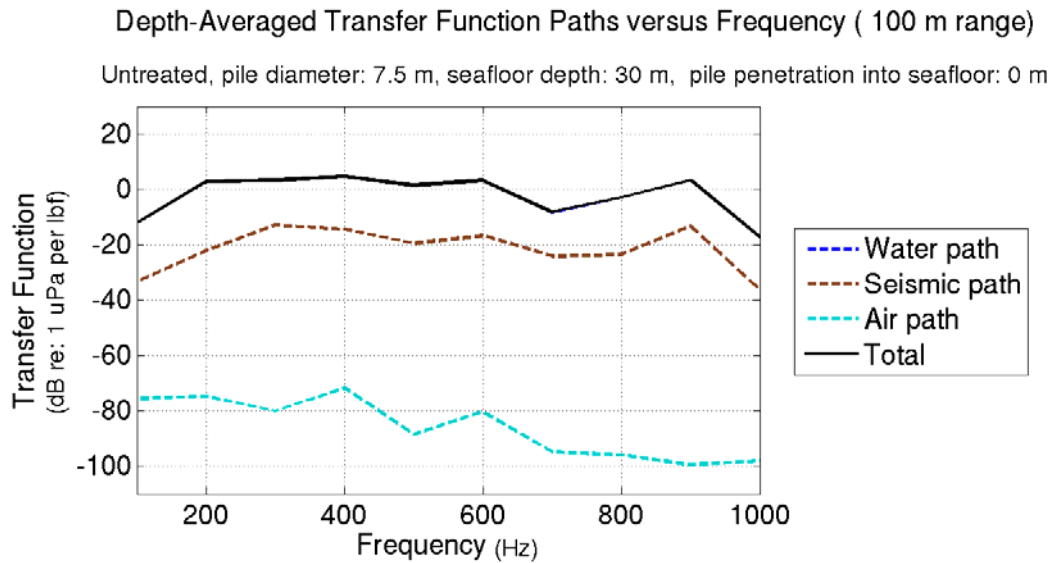


Fully driven



100 meter range from pile:

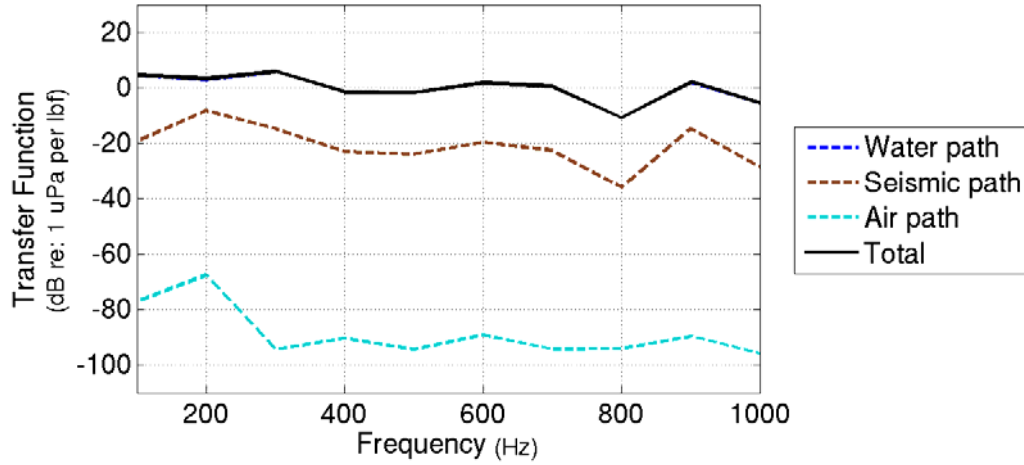
First contact with the ocean bottom



Halfway driven

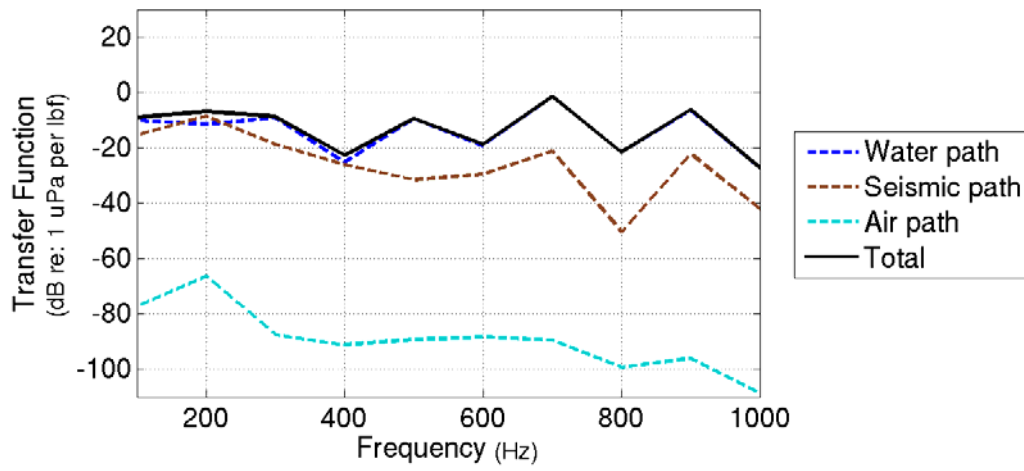
Depth-Averaged Transfer Function Paths versus Frequency (100 m range)

Untreated, pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



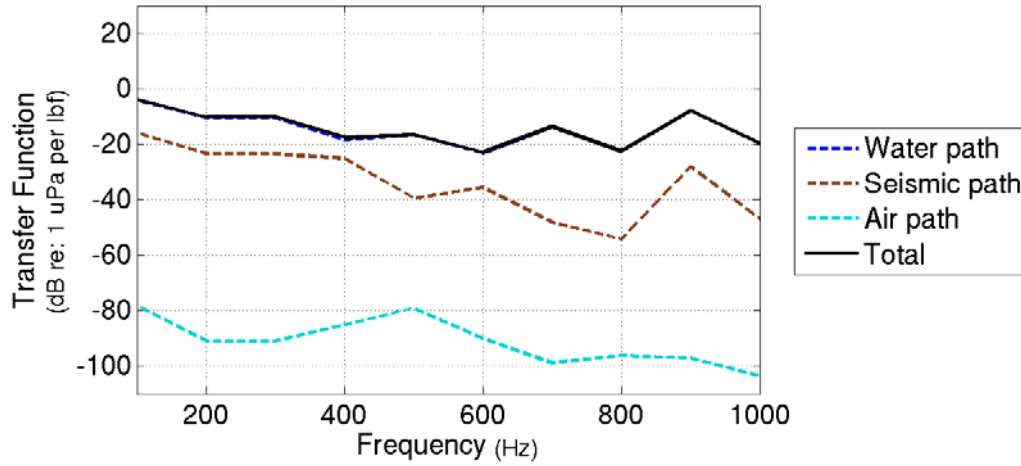
Depth-Averaged Transfer Function Paths versus Frequency (100 m range)

Bubble screen (5 %), pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



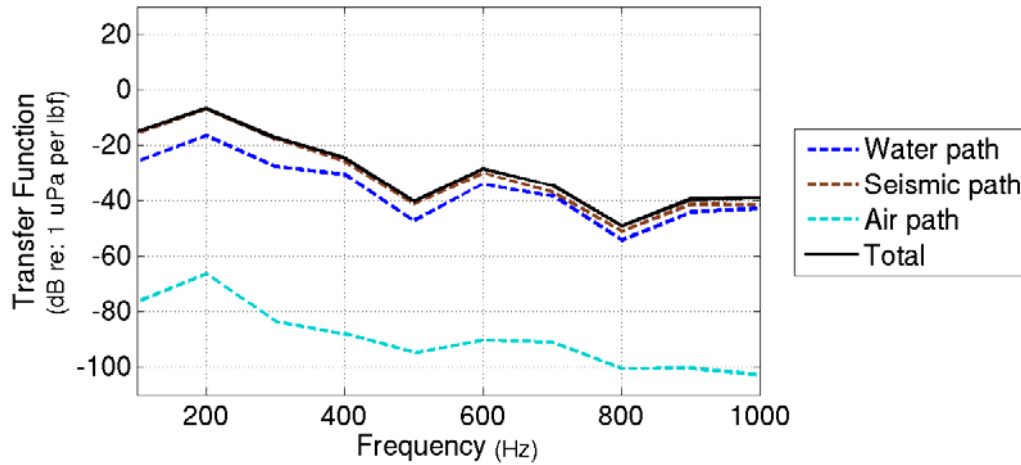
Depth-Averaged Transfer Function Paths versus Frequency (100 m range)

Rubatex (4 inch), pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



Depth-Averaged Transfer Function Paths versus Frequency (100 m range)

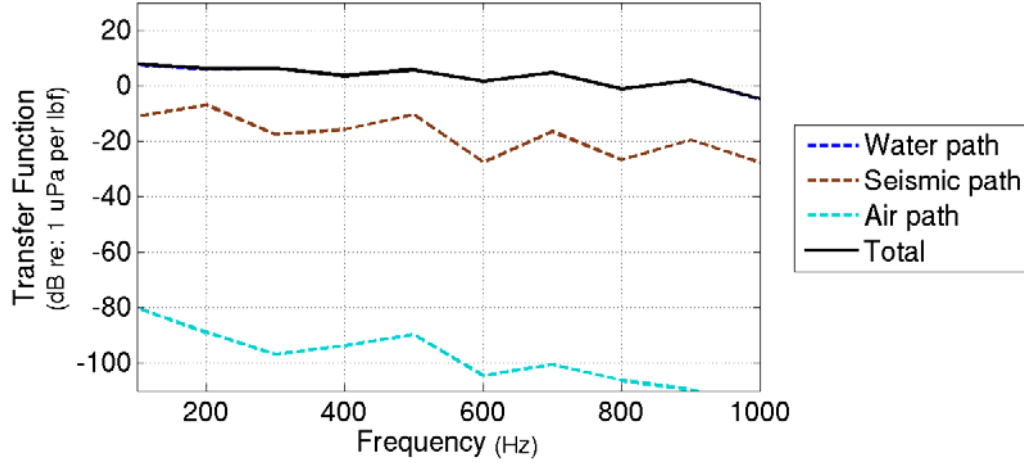
Cofferdam (type 2), pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



Fully driven

Depth-Averaged Transfer Function Paths versus Frequency (100 m range)

Untreated, pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 35 m

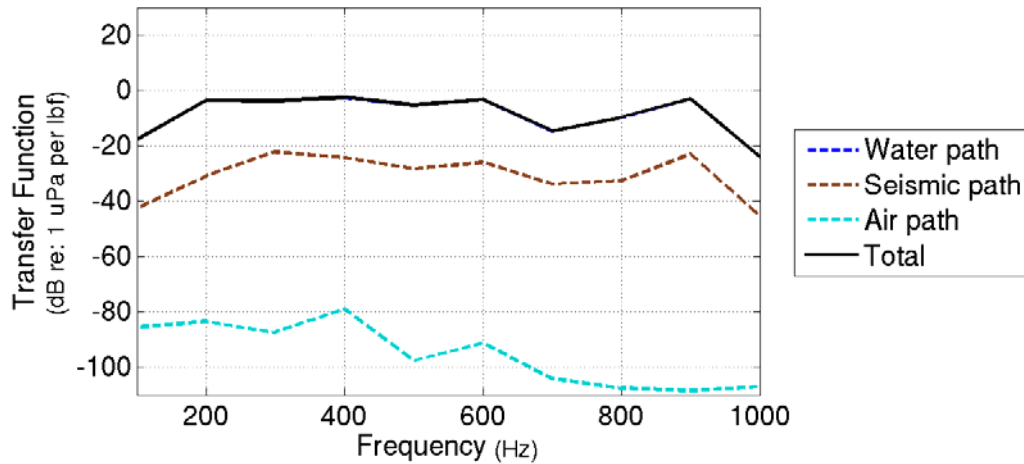


300 meter range from pile:

First contact with the ocean bottom

Depth-Averaged Transfer Function Paths versus Frequency (300 m range)

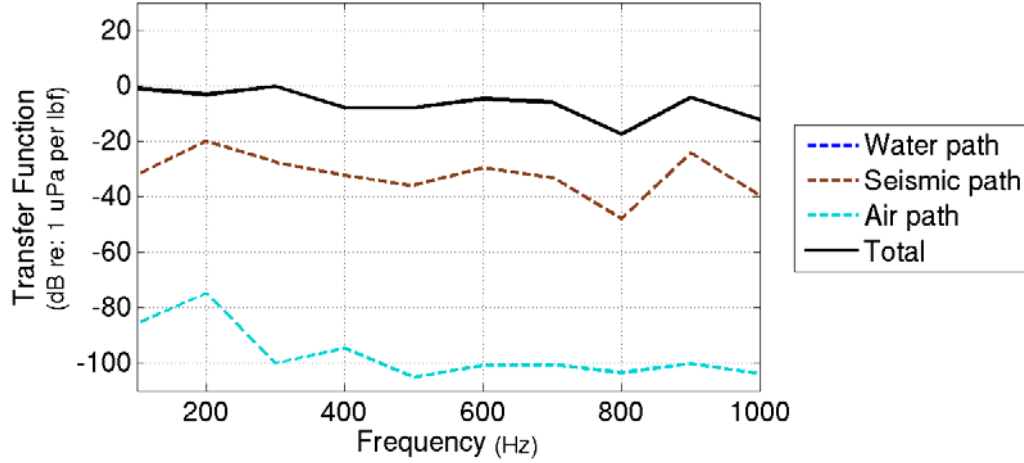
Untreated, pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 0 m



Halfway driven

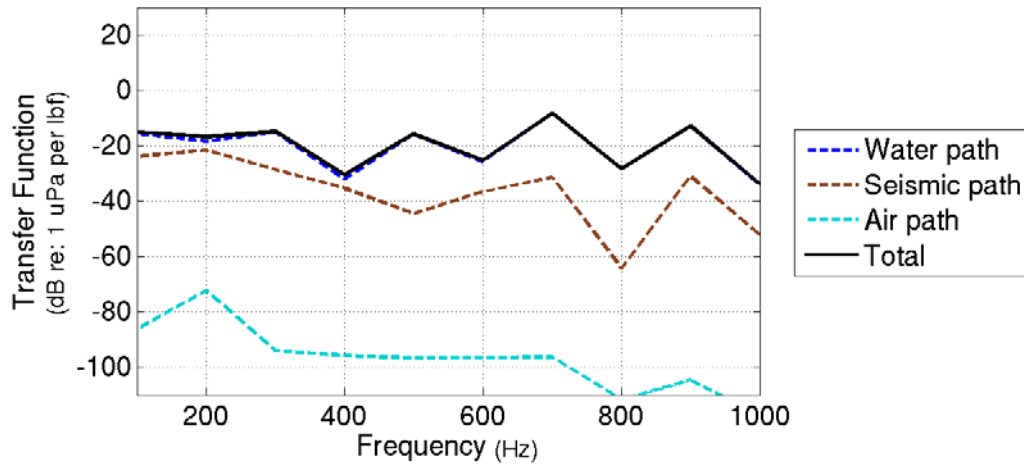
Depth-Averaged Transfer Function Paths versus Frequency (300 m range)

Untreated, pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



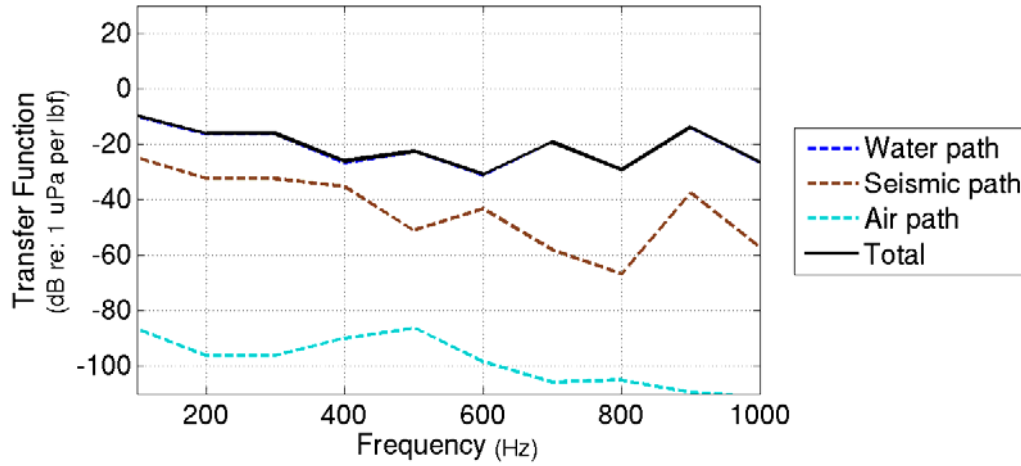
Depth-Averaged Transfer Function Paths versus Frequency (300 m range)

Bubble screen (5 %), pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



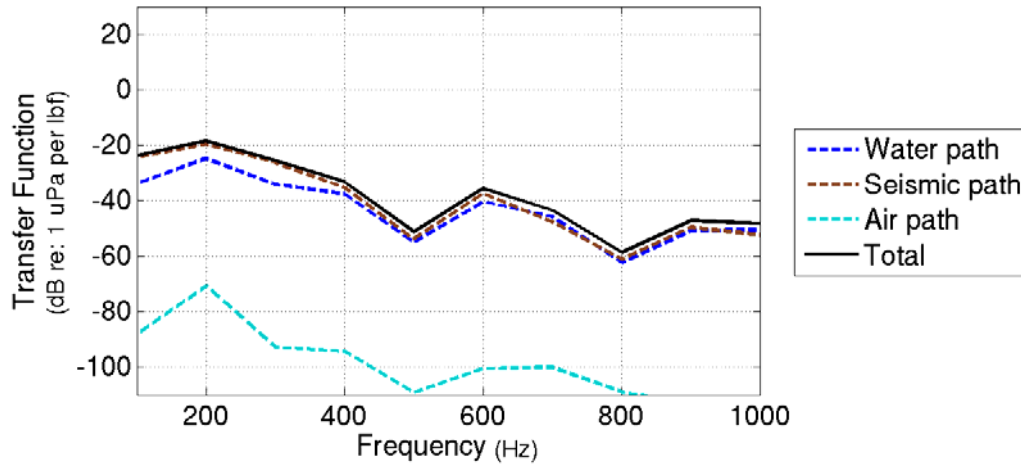
Depth-Averaged Transfer Function Paths versus Frequency (300 m range)

Rubatex (4 inch), pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



Depth-Averaged Transfer Function Paths versus Frequency (300 m range)

Cofferdam (type 2), pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 17.5 m



Fully driven

Depth-Averaged Transfer Function Paths versus Frequency (300 m range)

Untreated, pile diameter: 7.5 m, seafloor depth: 30 m, pile penetration into seafloor: 35 m

