Washington State
Department of Transportation

Memorandum

May 4, 2010

TO: John Callahan
Rick Huey

FROM: Jim Laughlin
(206) 440-4643

SUBJECT: Keystone Ferry Terminal – Vibratory Pile Monitoring Technical Memorandum.

Underwater Noise Levels

This memo summarizes the vibratory pile driving results measured at the Keystone Ferry Terminal in an effort to collect site specific data on underwater and airborne noise levels. The memo presents data collected during vibratory pile driving at the Keystone Ferry Terminal facility on Whidbey Island during the months of January and February 2010.

Four 30-inch diameter steel piles were monitored on three separate days as they were driven with an APE vibratory hammer. This report applies no frequency filter (*e.g.*, A-weighting or C-weighting) to the underwater acoustic measurements.

- Underwater sound levels quoted in this report are given in decibels relative to the standard underwater acoustic reference pressure of 1 microPa.
- Airborne noise levels were measured as un-weighted sound level. Airborne noise levels in this report use the acoustic reference pressure of 20 microPa.

The continuous sounds that frequently occur for extended periods associated with the use of a vibratory hammer may pruduce harassment-level take of ESA listed marine mammals. This harassment occurs when the sound exceeds the current 120 dB RMS NMFS threshold. Therefore, this memo adopts the 120 dB RMS threshold for the present analysis.

Measurement Locations

January 9, 2010

- Near field measurements were taken 10 meters from the pile in 30 feet of water on January 9, 2010. Far field measurements were taken at 279 meters from the pile in 30 feet of water depth (Figure 1). The far field location was inside of a strong current area just outside of the mouth of the harbor.
    - Two hydrophones deployed at 27 foot and 15 foot water depths measured the near field sounds.
    - One hydrophone deployed from the Autonomous Multichannel Acoustic Recorder (AMAR) approximately 21 feet from the bottom measured the far field sound.

January 17, 2010

- Near field measurements were taken at 11 meters from the piles being driven in 31 feet of water on January 17, 2010. Far field measurements were not collected due to equipment malfunction (Figure 1).
  - One hydrophone deployed 1 meter from the bottom measured the near field sounds.

February 8, 2010

- Near field measurements were taken 6 meters from the pile in 30 feet of water on February 8, 2010. Far field measurements were taken 546 meters from the pile in 94 feet of water (Figure 1). The far field location was just outside of the strong current area just outside of the harbor.
  - One hydrophone deployed in 15 feet water depth measured the near field sound.
  - One hydrophone deployed from the AMAR in approximately 85 feet water depth measured the far field sound.

Figure 1: Location of near field and far field monitoring locations at the Keystone Ferry Terminal.

No noise mitigation was utilized as part of these vibratory measurements. Broadband (0 Hz to 10 kHz) Root Mean Square (RMS) noise levels are reported in terms of the 30-second average continuous sound level computed from the Fourier transform of the pressure waveforms in 30-second time intervals.

Near Field Measurements

- Average RMS values ranged from 164 to 176 dB RMS at the near field location with an overall average RMS value of 171 dB RMS. Distances from hydrophone to pile ranged between 6 and 11 meters.
- Table 1 summarizes the results of the near field measurement locations for each pile monitored.

Table 1: Summary Table of Underwater Monitoring Results at the Near Field Location.

Pile #	Date	Hydrophone Depth	Distance To Pile (meters)	Absolute Peak (dB)	Average RMS Value (dB)
1	1/9/10	15 feet (midwater)	10	195	164
		27 feet (bottom)	10	195	165
2	1/17/10	29 feet (bottom)	11	195	176
3	2/8/10	15 feet (midwater)	6	200	176
4		15 feet (midwater)	6	176	165
			Overall Average:	**196**	**171**

The results of Table 1 show average RMS values around 171 dB RMS in the near field for most piles. Average RMS values are appropriate for continuous sounds generated during vibratory driving.

AMAR Far Field Measurements

In addition to the near shore noise measurements, analysts measured far field sound levels at distances of 279 meters (Deployment Site 1) and 546 meters (Deployment Site 2) using an Autonomous Multi-Channel Acoustic Recorder (AMAR mini) from Jasco Reasearch Ltd. in Canada. WSF is using the AMAR to determine the accuracy of the estimated range of impacts to marine mammals according to the NMFS underwater threshold of 120 dB RMS. WSF is concerned that the practical spreading model used by NMFS is overly conservative and hopes to use site specific information collected with the AMAR to develop a more appropriate model (e.g. spherical or cylindrical). It is hoped that for some WSF projects the AMAR will allow a fine tuning of the threshold boundary during the very early stages of future projects.

For this project, the AMAR was deployed at different depths and distances to monitor the vibratory pile driving effort: 279 meters (915 feet) on January 9th for pile 1 and 546 meters (1791 feet) for piles 3 and 4 on February 8th (Figure 1). The nearer location was positioned just inside of the strong current area just outside the mouth of the harbor. The AMAR only collected background data at the 279 meter location. Due to an equipment malfunction no vibratory data was collected for Piles 1 and 2. The farther location was positioned just outside of the strong current area just outside the mouth of the harbor. This location would help determine if the strong current had an appreciable effect on the transmission loss as the noise passed through this strong current area. However, without the vibratory data from Piles 1 and 2 it is difficult to make this comparison.

Table 2: Summary table of underwater AMAR monitoring results at the far field locations.

Pile #	Hydrophone Depth[1]	Date	Distance To Pile (meters)	Absolute Peak (dB)	Average RMS Value (dB)	Transmission Loss[2]
1	21 feet	1/9/10	279	No Data Collected		
2	85 feet	1/17/10	546	No Data Collected		
3[3]	85 feet	2/8/10	546	168	156	20
4[3]	85 feet	2/8/10	546	168	158	7
Overall Average				**168**	**157**	**13.5**

[1] – Depth represents depth as measured from the surface. In all locations the hydrophone was deployed approximately 13 feet above the bottom.

[2] - Transmission loss (TL) is a complicated function of local bathymetry, sound-speed profile, range, source frequency, absorption, and scattering (Medwin and Clay, 1998). However, if it is possible to measure both the source and received sound pressure levels, the equation below may be used to calculate the transmission loss (Carr et al., 2006).

[3] – A larger vibratory hammer was used for this pile than for Pile 1.

Note: $TL_{dB} = SL_{dB} - RL_{dB}$; where SL_{dB} is the measured source level and RL_{dB} is the measured received level

Based on the results of Table 3 WSF proposes that the cylindrical model best fits the vibratory data for the Keystone project at least within the harbor, however, because the cylindrical model is highly conservative and is likely only functioning within the harbor itself, WSF proposes the use of the conservative practical spreading model for Keystone instead. The bullets below describe a comparison of the two models using actual measured data.

- Practical Spreading Model: Assessing the 120 dB RMS threshold from the Pile 3 and 4 locations at 6 meters and measuring the highest and most conservative measured 158 dB RMS value at the far field location, the NMFS marine mammal calculator results in a threshold boundary 116 miles from the pile (i.e., 158 dB RMS measured at the AMAR location 0.34 miles from the pile to the 120 dB RMS threshold for a total of 116 miles).
- Cylindrical Model: Using the most conservative average RMS value of 158 dB RMS for Pile 4 and inputting it into the NMFS calculator for marine mammal thresholds, the sound levels should reach the 120 dB RMS threshold at approximately 2,140 miles (i.e., 158 dB RMS measured at the AMAR location 0.34 miles from the pile the 120 dB RMS threshold

is reached 2,140 miles from the AMAR).

Based on measurements at the Keystone terminal, we used the transmission loss values from Table 2 and calculated the distance in meters to the measured sound level (dB RMS) using the practical, cylindrical and spherical spreading models.

Practical Spreading Model: $R_1 = R_0 * 10^{(TL/15)}$
Spherical Spreading Model: $R_1 = R_0 * 10^{(TL/20)}$
Cylindrical Spreading Model: $R_1 = R_0 * 10^{(TL/10)}$

According to the results in Table 3 the practical spreading model appears to under predict the actual measured values since it predicts that the measured sound level would occur at 0.05 miles instead of 0.34 miles. All three models under predict the measured values. Comparing the measured AMAR results at 0.34 miles (546 meters) for Piles 3 and 4 using the practical, spherical and cylindrical spreading models it appears, that on average, the cylindrical comes closest to predicting the actual measured value (differing by an average distance of 739 feet or 0.14 miles (0.34 mi. – 0.20 mi = 0.14 mi)). This is likely due to the relatively flat and smooth bottom, relatively shallow water and constant depth of the harbor at Keystone.

Table 3: Comparison of different spreading models using actual measured data.

Spreading Model	Distance From Pile (meters)	Pile #	Transmission Loss[1]	Calculated Meters To Measured dB RMS	Calculated Miles To Measured dB RMS	Measured Distance at Measured dB RMS (miles)
Practical	6	3	20	129	0.08	0.34
	6	4	7	30	0.01	0.34
				Average	**0.05**	**0.34**
Spherical	6	3	20	60	0.04	0.34
	6	4	7	13	0.01	0.34
				Average	**0.03**	**0.34**
Cylindrical	6	3	20	600	0.37	0.34
	6	4	7	30	0.02	0.34
				Average	**0.20**	**0.34**

[1] - $TL_{dB} = SL_{dB} - RL_{dB}$; where SL_{dB} is the measured source level and RL_{dB} is the measured received level

AMAR Background Measurements

Broadband background measurements between 0 Hz and 10 kHz were collected on January 9, 2010 when there were no ferry vessels present during the daytime due to construction activities (Figure 2). Additional broadband background measurements were collected on February 8, 2010 when ferry vessels were present.

Background noise levels during the daytime in the absence of ferry traffic are dominated by noise from nearby water currents and in the presence of ferry traffic dominated by nearby vessel traffic. Broadband Root Mean Square (RMS) background noise levels are reported in terms of the 30-second average continuous sound level and have been computed from the Fourier transform of pressure waveforms in 30-second time intervals. Background levels were measured at 790 meters from the piles using the AMAR system which has a more sensitive hydrophone.

Broadband background sound levels on January 9, 2010 collected between 2: 46 PM and 3:04 PM in between pile driving activities indicate that the overall average background RMS level is 118 dB RMS with no ferry vessels present. Therefore, in the absence of ferry vessel traffic the vibratory driving noise levels will not attenuate to background levels before they reach the 120 dB RMS threshold.

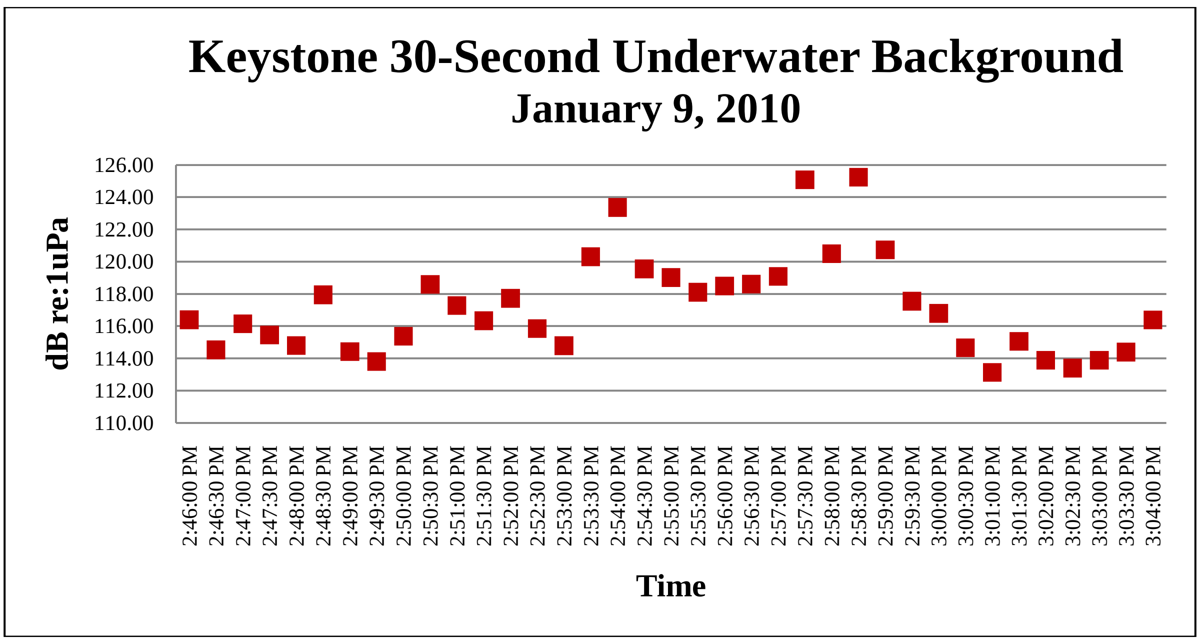

Figure 2: Hourly average broadband background RMS values collected on January 9, 2010, 0.17 miles from the Keystone Ferry Terminal. Average background is 118 dB RMS without ferry vessels present.

The overall average broadband background sound levels collected February 8, 2010 between 2:02 PM and 3: 50 PM in between pile driving activities is 144 dB RMS (Figure 3). Therefore, calculating the threshold to 144 dB RMS background levels it would be an average of 0.3 miles from the source using the practical spreading model or approximately where the AMAR is located. Using the cylindrical spreading model the source would attenuate to 144 dB RMS at an average of 3.2 miles from the source. In comparison, the modeled distance to the 120 dB RMS threshold using the practical spreading model before we had the site specific data was 39 miles.

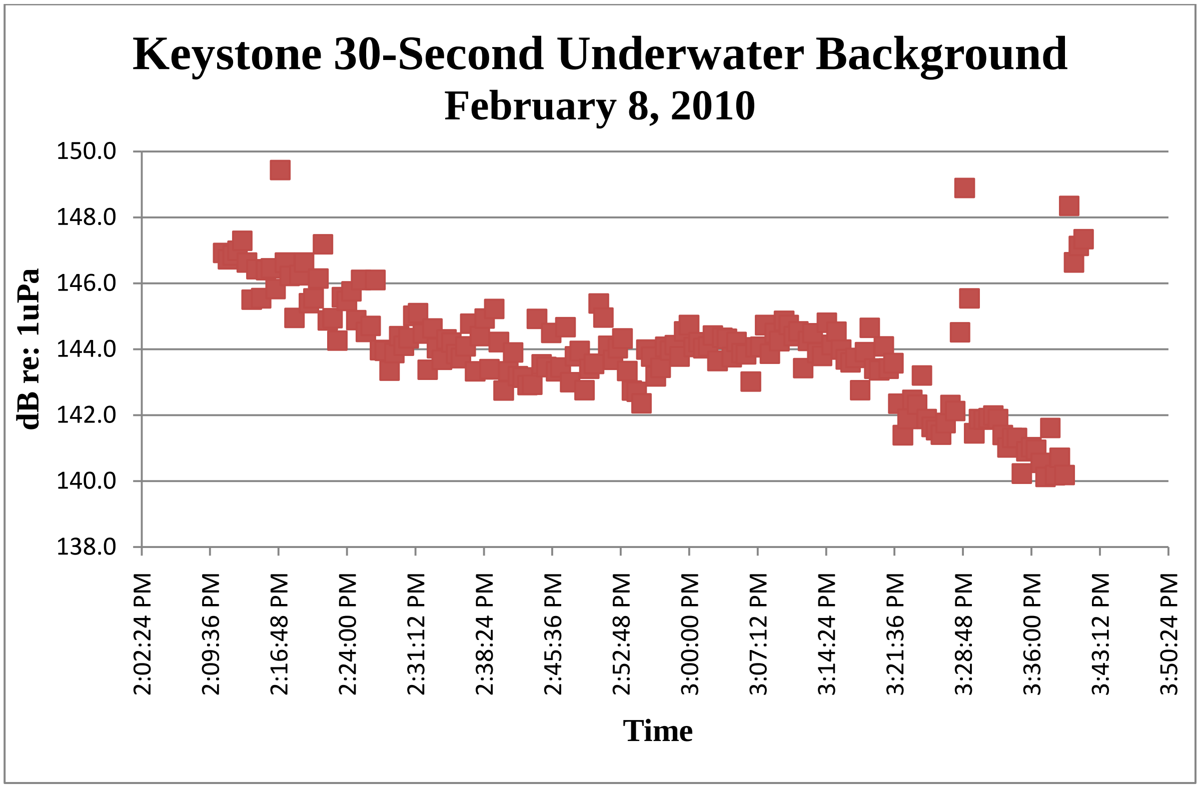

Figure 3: Hourly average broadband background RMS values collected on February 8, 2010, 0.34 miles from the Keystone Ferry Terminal. Average background is 144 dB RMS with ferry vessels present.

The bottom bathymetry is relatively shallow within the harbor (approximately 30 feet of water depth until you reach the mouth of the harbor). Then it drops off slowly beyond the mouth. This is not typical of most of the ferry terminal locations and could explain why the cylindrical model is better at predicting the attenuation of noise from vibratory pile driving at Keystone.

However, care should be taken to consider differences in the acoustic environment when extrapolating propagation loss estimates from the Keystone Ferry terminal site to other locations. As with all empirically derived transmission loss laws, the cylindrical spreading law suggested for the Keystone site should only be extrapolated to similar acoustic propagation environments.

Comparison of Near Field and Far Field Underwater Measurements

Figures 4 through 7 show the relative differences between the near field RMS values, the far field RMS values and the background RMS values for Piles 1 through 4, respectively. As the figures indicate, the near field RMS values are somewhat variable, whereas the far field and background average measurements are much less variable. For piles 3 and 4 the far field measurements were very close to the near field levels due to the relatively shallow and constant bathymetry between the source and the received level.

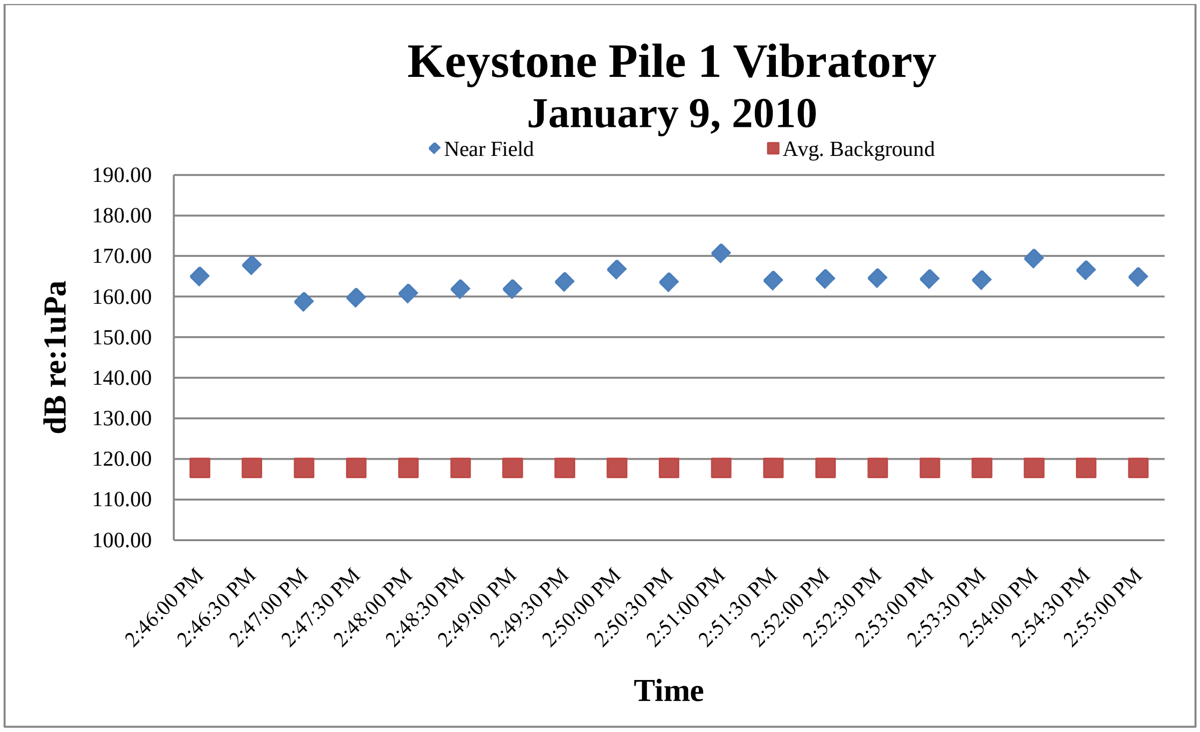

Figure 4: Pile 1 - Comparison of Vibratory Root Mean Square Values (RMS) at 30-second intervals for 10 meters from the pile and background. No vibratory data was collected for this pile at the 279 meter location.

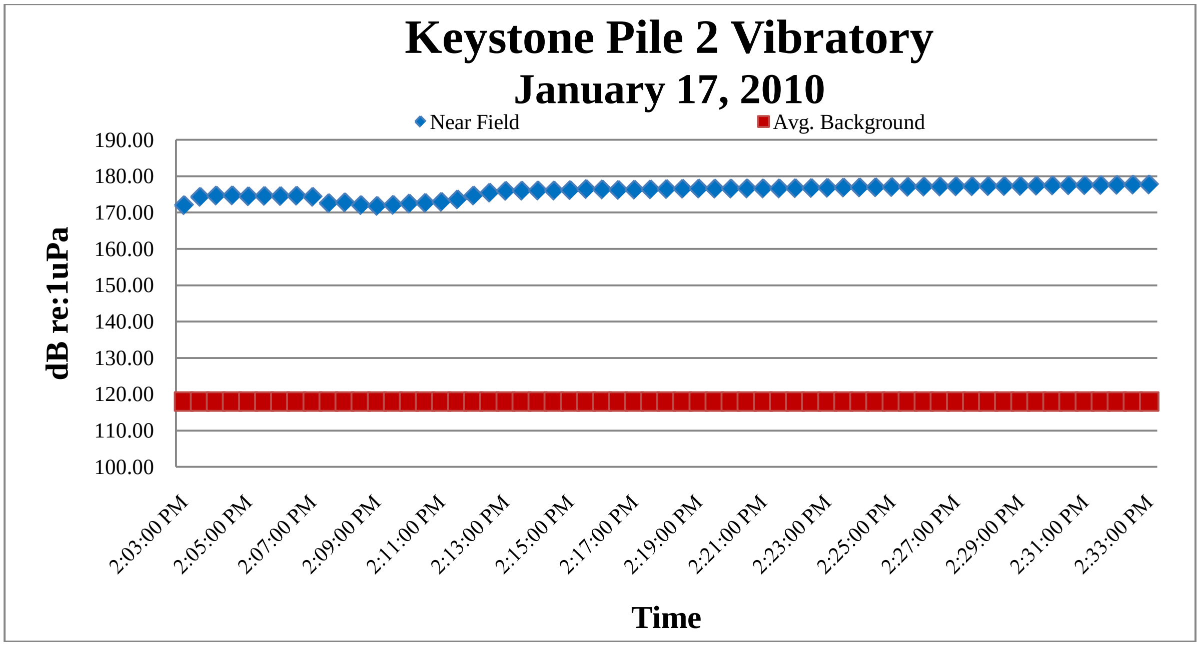

Figure 5: Pile 2 - Comparison of Vibratory Root Mean Square Values (RMS) for 11 meters from the pile and average background data collected from January 9, 2010.

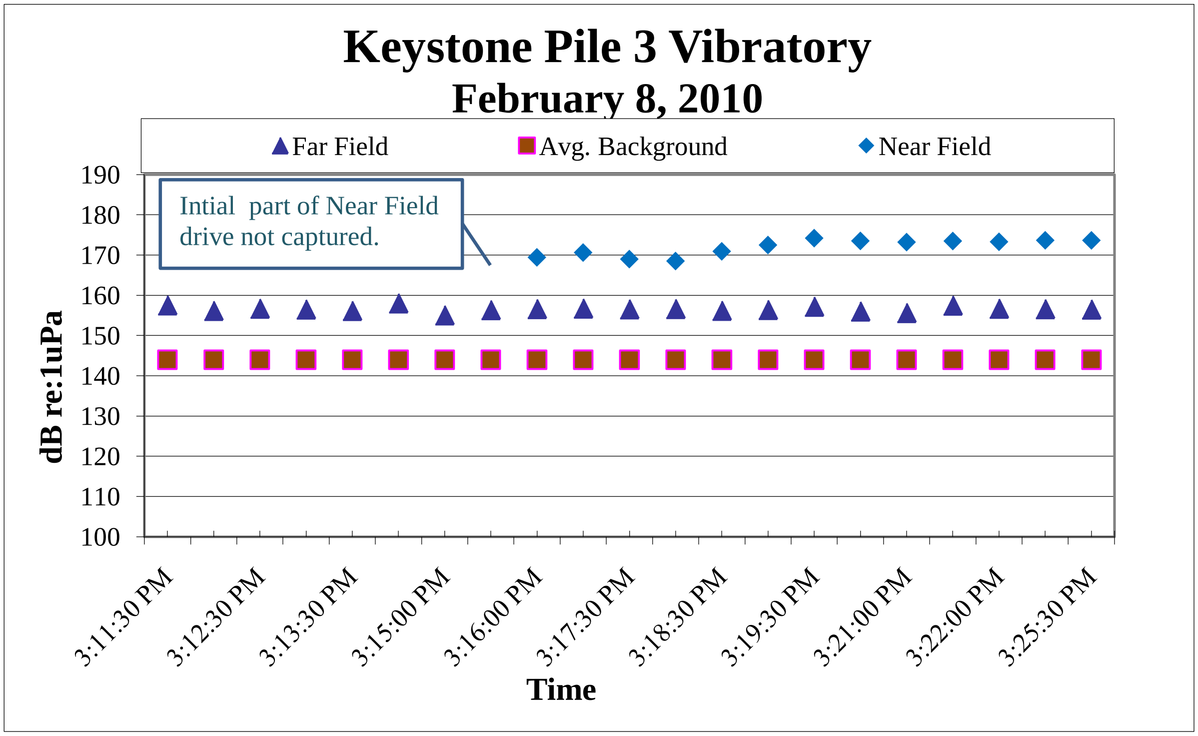

Figure 6: Pile 3 - Comparison of Vibratory Root Mean Square Values (RMS) for 6 meters and 546 Meters from the pile. Background RMS values are also included.

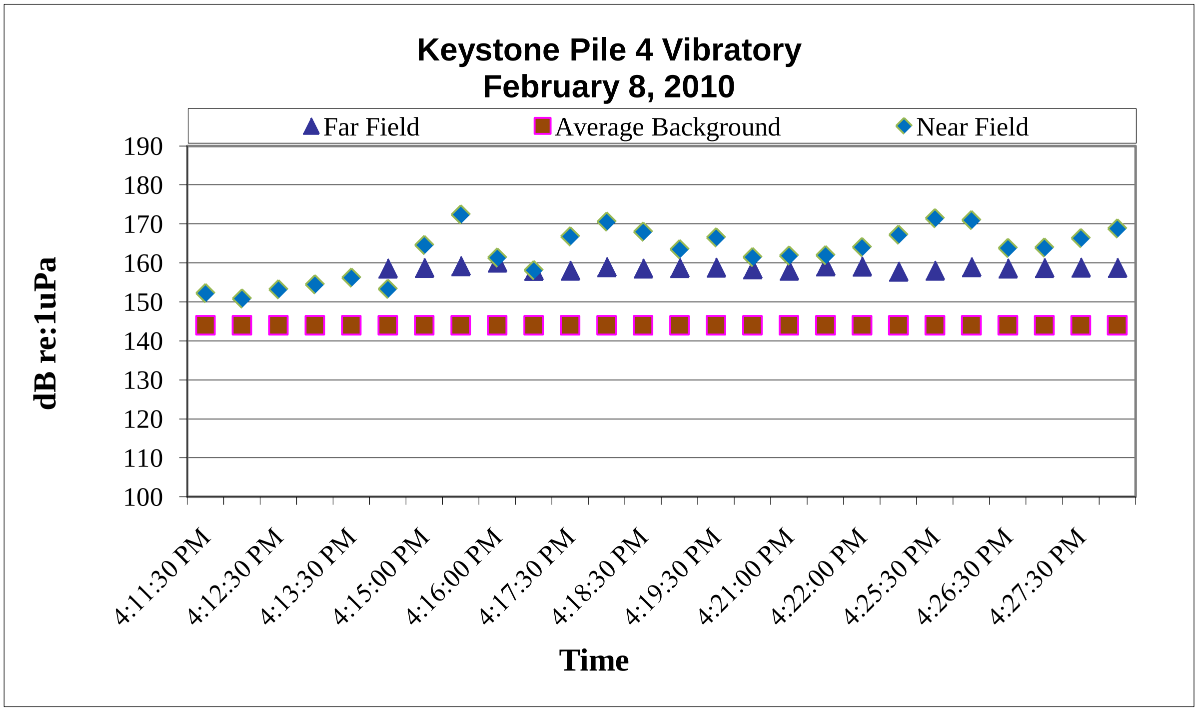

Figure 7: Pile 4 - Comparison of Vibratory Root Mean Square Values (RMS) for 6 meters and 546 Meters from the pile. Background RMS values are also included.

Airborne Noise Levels

Airborne noise levels were measured for Pile 1 at the same time as underwater monitoring of the vibratory driving. Noise levels from this pile is measured in terms of the 5-minute average continuous sound level (5-minute Leq) and described in Table 4:

$$\textbf{(5 min)} \quad L_{eq} = 10\log\left(\frac{1}{T}\int_T p(t)^2\,dt\right)$$

Where p(t) is the acoustic overpressure, T = 5 minutes and 0 < t < T.

RMS values are calculated by integrating the sound pressure averaged over some time period, in this case 5-minutes in a similar way that the Leq values are calculated. Therefore, in this instance the 5-minute Leq is the same as the RMS sound pressure level over a 5-minute period (Table 4). The 5-minute Leq and Lmax levels were measured without any weighting applied (unweighted). Four consecutive replicate measurements were collected. The overall average unweighted RMS level is 98 dB and the overall average unweighted Lmax is 104 dB.

Table 4: Summary Table of Airborne Monitoring Results.

Pile #	Replicate	Distance from Pile (meters)	Unweighted Leq/RMS (dB)	Unweighted Lmax (dB)
1	1	11	98	102
	2	11	96	101
	3	11	97	105
	4	11	99	106
Average			**98**	**104**

Figure 8 shows the 1/3rd octave frequency distribution for the unweighted Leq metric for Pile 1 driven with a vibratory hammer and four separate replicate measurements. Figue 8 show:

- All measurement have very similar distributions with slight variability in the lower frequencies below 500 Hz.
- The dominant frequency for all piles is between 315 and 500 Hz.

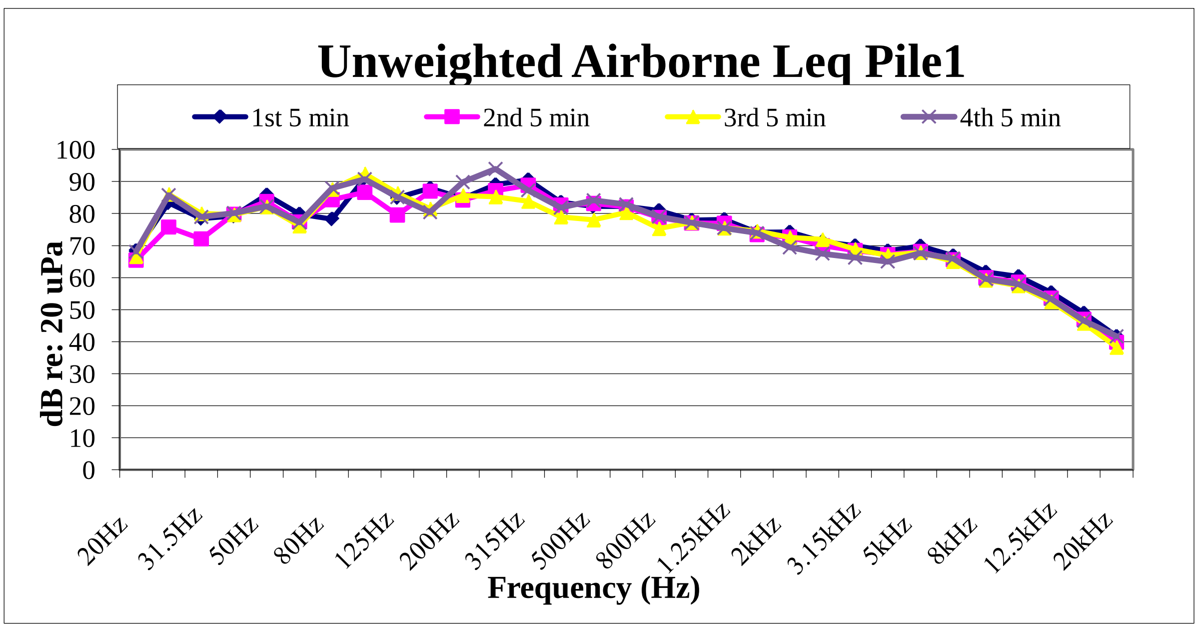

Figure 8: Pile 1 – Comparison of unweighted frequency distribution for the Leq metric using a vibratory hammer.

Figure 9 shows the 1/3rd octave frequency distribution for the unweighted Lmax metric for Pile 1 and each of four replicate measurements while the pile is driven with a vibratory hammer. This figure also shows:

- All four replicates have a similar distribution at all frequencies with some slight variability below 500 Hz.
- The dominant frequency for all replicates is around 315 Hz.

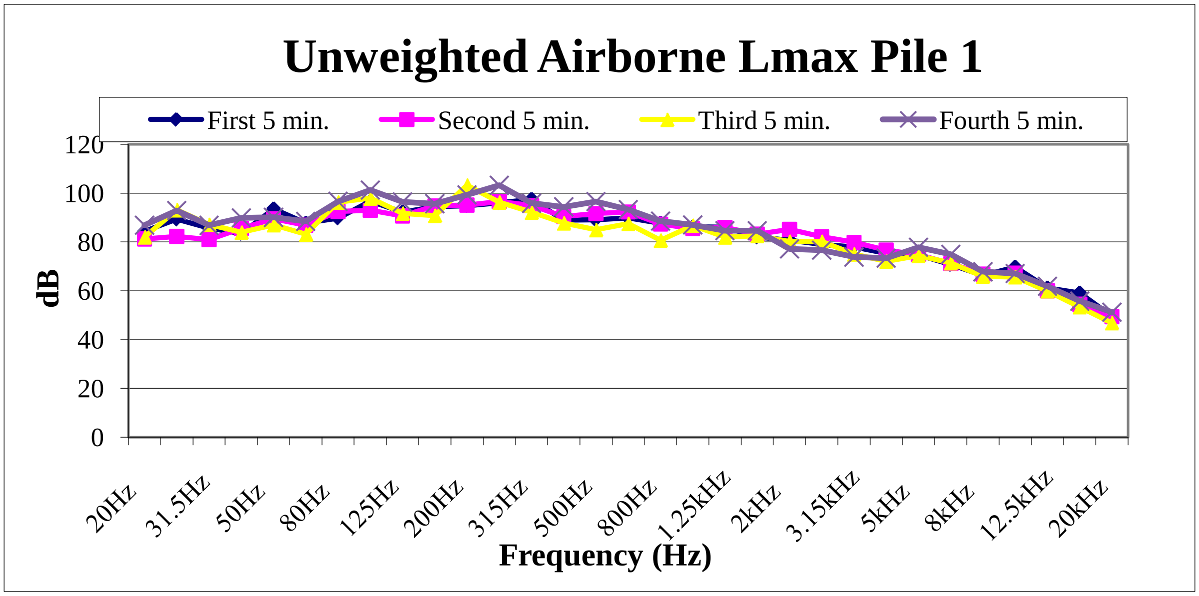

Figure 9: Pile 4 - Comparison of A-weighted frequency distributions for the Lmax metric using a vibratory hammer.

Conclusions

Near and far field underwater measurements were taken in addition to some underwater background measurements and airborne measurements at the Keystone Ferry terminal during vibratory pile driving. The far field measurements were designed to determine the accuracy of the modeled underwater threshold boundary for marine mammals. RMS values measured at the near field location were lower than previous vibratory measurements made in Puget Sound.

The far field measurements indicate that the RMS values attenuate more quickly than estimated using the practical spreading model. Average transmission loss over the 0.34 mile distance to the far field site was 13.5 dB but highly variable. The highest average RMS value measured at the far field site was 158 dB RMS. Using these values the practical spreading model underestimates the actual distance to the measured far field site by 0.29 miles. The cylindrical spreading model came closest to estimating the actual transmission loss measured while still under predicting where the measured value would occur. This is likely due to the relatively flat smooth bottom topography in Keystone Harbor and constant water depth.

Background measurements were taken at the far field location with the AMAR system. Background levels ranged from an average of 118 dB RMS with no ferry traffic present to an average of 144 dB RMS with the presence of ferry traffic. This value is somewhat higher than that reported previously at near shore locations in Puget Sound. However, it was determined that the vibratory sound levels will attenuate to the background level before reaching the 120 dB RMS marine mammal threshold.

While it is interesting that when using the measured data, the cylindrical spreading model more accurately predicts the measured noise levels overall, WSF is not proposing to use the cylindrical spreading model. WSF believes that this result is due to the relatively shallow water depth and smooth flat bottom topography of the harbor, and does not represent how in-water noise will behave when it reaches deeper water outside of the harbor. Therefore, WSF will continue to use the default practical spreading model at the Keystone ferry terminal since it is still a conservative estimate. Using the higher RMS values creates the best conservative estimate of the threshold boundary.

The airborne noise measurements may be the first airborne measurements of vibratory driving operations in Puget Sound and are certainly the first unweighted airborne measurements. The values ranged from 96 dB to 99 dB RMS. 1/3rd octave band frequency measurements were collected and indicated that each replicate measurement had little variability.

If you have any questions please call me at (206) 440-4643.

(jl):(jl)

Attachments
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Literature Cited

Carr, Scott A., Marjo H. Laurinolli, Cristina D. S. Tollefsen and Stephen P. Turner. 2006. Cacouna Energy LNG Terminal: Assessment of Underwater Noise Impacts. Jasco Research Ltd., pp. 63.

Medwin, H., and Clay, C. S. (1998) Fundamentals of Acoustical Oceanography. Academic Press, Toronto.

Near Field Single Strike Waveform Analysis

Keystone Pile 1 - Midwater

Figure a. Waveform

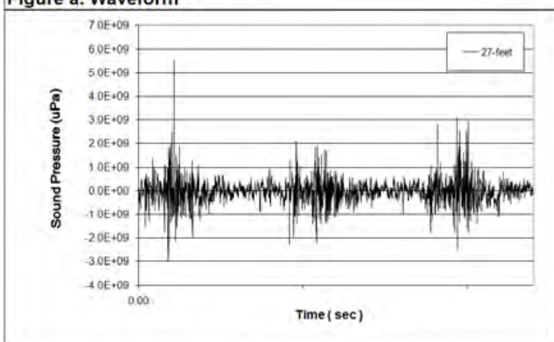

Figure b. Narrow Band Frequency Spectra

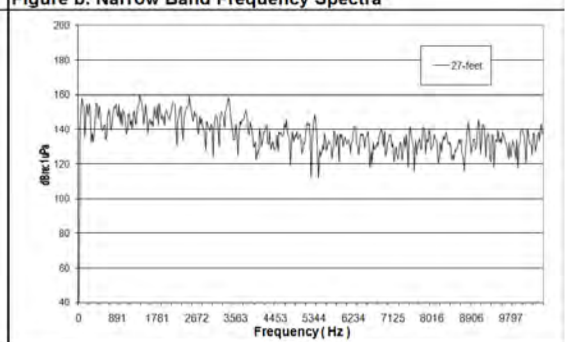

Figure c. Accumulation of Sound Energy

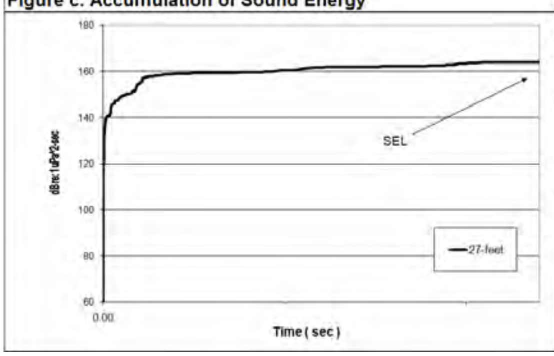

Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

meters from pile - 00:00	Peak	RMS90%*	SEL
27-feet	195	175	164

*Impulse averaged over 90% of accumulated energy (5% to 95%)

Keystone Pile 1 - 1 meter from bottom

Figure a. Waveform

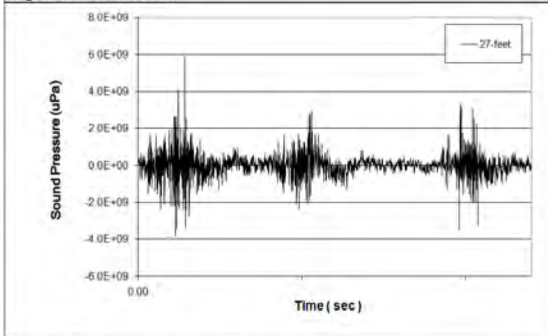

Figure b. Narrow Band Frequency Spectra

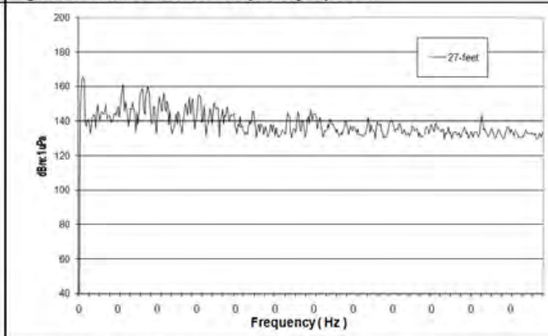

Figure c. Accumulation of Sound Energy

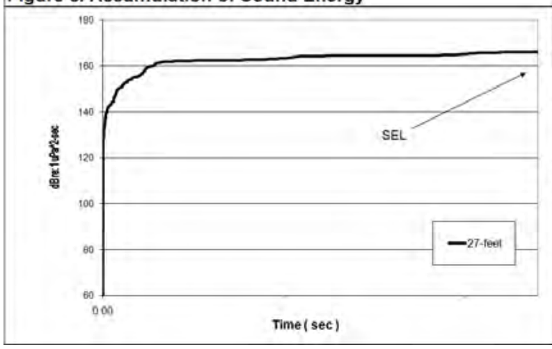

Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels			
meters from pile - 00:0	Peak	RMS$_{90\%}$*	SEL
27-feet	195	176	166

*Impulse averaged over 90% of accumulated energy (5% to 95%)

Keystone Pile 2 - Bottom

Figure a. Waveform

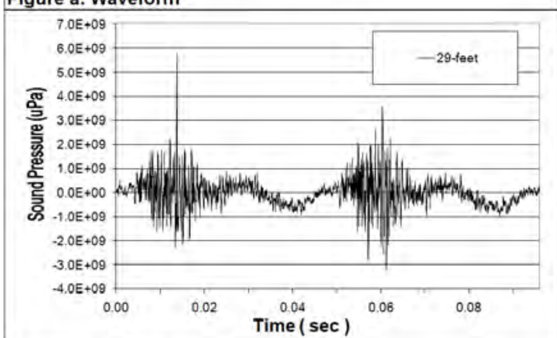

Figure b. Narrow Band Frequency Spectra

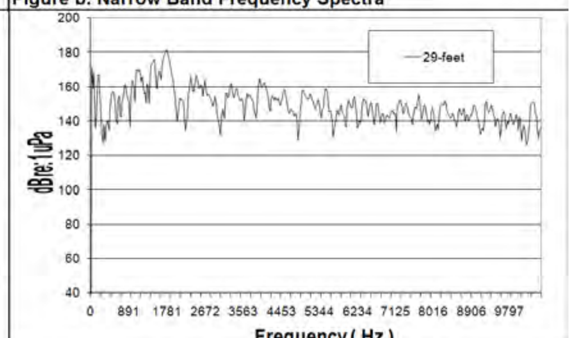

Figure c. Accumulation of Sound Energy

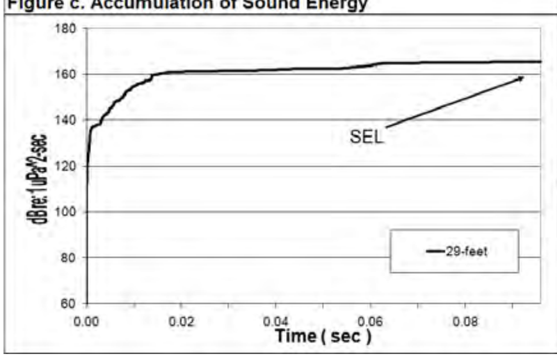

Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels			
meters from pile - 00:0	Peak	RMS$_{90\%}$*	SEL
29-feet	195	176	165

*Impulse averaged over 90% of accumulated energy (5% to 95%)

Keystone Pile 3 - Midwater

Figure a. Waveform

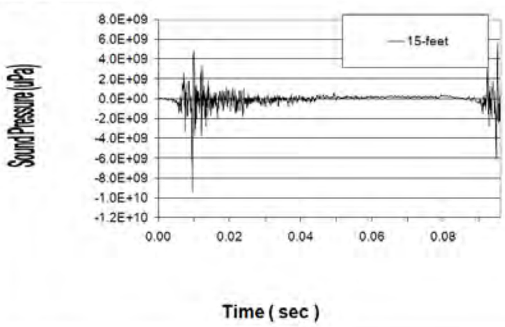

Figure b. Narrow Band Frequency Spectra

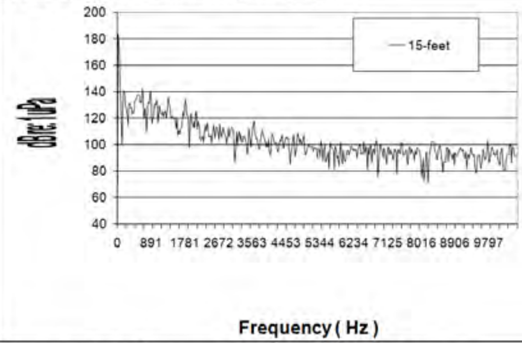

Figure c. Accumulation of Sound Energy

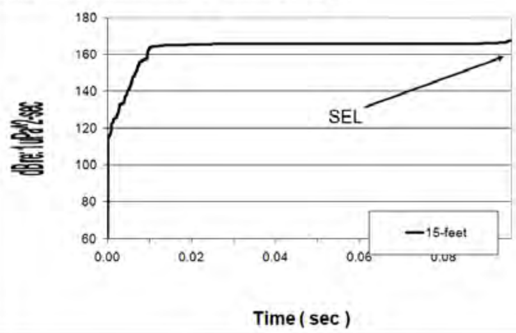

Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

neters from pile - 00:00	Peak	RMS90%*	SEL
15-feet	200	177	167

*Impulse averaged over 90% of accumulated energy (5% to 95%)

Keystone Pile 4 - Midwater

Figure a. Waveform

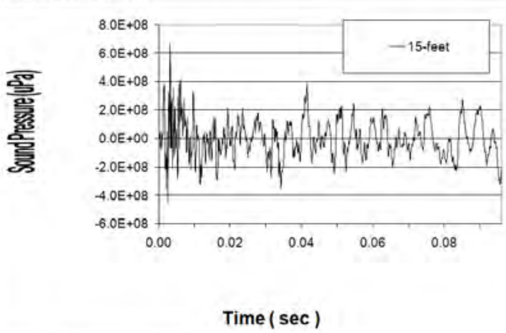

Figure b. Narrow Band Frequency Spectra

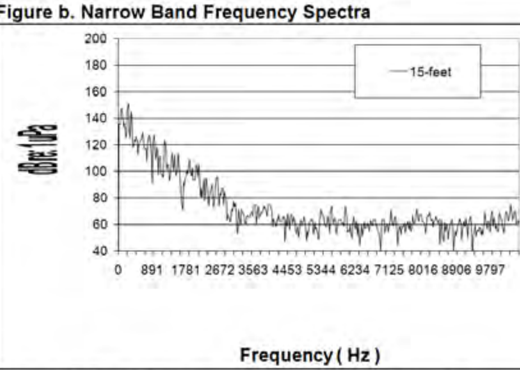

Figure c. Accumulation of Sound Energy

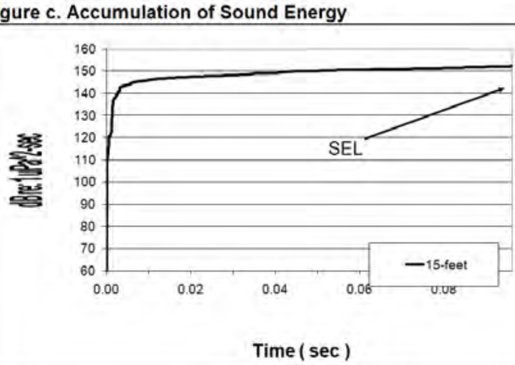

Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

neters from pile - 00:00	Peak	RMS90%*	SEL
15-feet	176	162	152

*Impulse averaged over 90% of accumulated energy (5% to 95%)