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Development and Implementation of an Underwater Construction Noise Program

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ABSTRACT

Concern for the welfare of and avoidance of noise impact to marine species is becoming an ever-greater requirement for construction projects. State agencies and infrastructure projects along the US West Coast have been concerned with protecting fish and marine mammals for decades, but we are now seeing projects along the US East Coast starting to adopt similar regulations and requirements in greater number. This paper will describe the development and implementation of an underwater noise mitigation program for a major new bridge construction project in the Mid-Atlantic States. The paper will include a description of the project; the need to protect certain species; the development of an underwater noise specification; the instrumentation and data collection methods used on this project; the results for vibratory/impact pile driving and caisson drilling; a discussion of mitigation measures including a bubble curtain; and the lessons learned from the project, most notably the need for a standard definition of cumulative sound exposure level (cSEL).

1. INTRODUCTION

Construction projects and equipment are inherently noisy. Noise from operations such as pile driving, hoe ramming and blasting can be particularly loud. But “loud” according to whom; as noise is perceived “in the ear of the beholder”. For the vast majority of construction projects emphasis has been placed on managing, measuring and controlling air-borne noise (and ground-borne vibration) because it can affect the health and quality of life of humans. However, other living species such as birds, marine mammals and fish are also exposed to construction noise so concern should be applied towards protecting them as well.

Construction projects along the West Coast of the United States have had specifications and provisions in them to minimize and monitor underwater noise for decades now. Bridge construction projects over salt water bays and rivers routinely identify sturgeon and sea turtles as species requiring protection from excessive noise. Concern for other species, such as smelt, herring, salmon, dolphin and seals, are also found in West Coast specifications. Projects along the East Coast have lagged behind in these regards. However, there are an increasing number of projects that are addressing underwater noise control, particularly as it might impact protected or endangered aquatic species. In general, underwater noise control is concerned with two different levels of potential impact: (1) noise loud enough to startle or adversely affect the natural behavior, feeding or reproductive habits of certain species, and (2) noise loud enough to potentially cause injury or even kill certain fish and marine mammals. The paper will describe noise criteria for both levels of impact concern.

2. PROJECT DESCRIPTION

The project used as an example in this paper is a major bridge construction project in one of the Mid-Atlantic States, shown in Photo 1. The project is currently well underway and is expected to take 6 to 7 years to complete at a cost of $318 million. The work involves building a new 4-lane bridge immediately adjacent to an existing one (shown in picture), rehabilitating the existing main and auxiliary bridges, and related intersection improvements.

Photo 1. Example Bridge Project

Noisy work occurring directly in the water will include impact and vibratory pile driving and caisson drilling. To this end the State DOT has identified Atlantic sturgeon and sea turtles as species of concern, and directed the project to develop and implement an acceptable underwater noise monitoring and mitigation program.

3. UNDERWATER NOISE SPECIFICATION

An underwater noise specification was required for this project with the specific intent of protecting Atlantic sturgeon and sea turtles from excessive construction noise. Like any worthwhile construction specification, this one would need to clearly define the contractor's obligations, required submittals, equipment and time restrictions, measurable performance criteria, required mitigation measures, and consequences for noncompliance.

Rather than develop a specification from scratch, a review was first performed of similar specifications and guidelines used on several West Coast construction projects. To this end, some of the compendium publications available from the California Department of Transportation were particularly helpful.

It became clear that it would be necessary to adopt different noise metrics for this project in order to properly address potential effects from continuous and transient noise sources, and that different limits would be needed based on the affected species types. As shown in Table 1, two noise criteria thresholds were adopted for this project's specification; one to avoid behavior disturbance and another to avoid injury or death of sturgeon and sea turtles. The specified decibel levels are referenced to 1 micro-Pascal (typical for underwater noise) and are unweighted over the frequency range of 20 Hz to 10,000 Hz at an evaluation distance of 10 meters (33 feet) from the noise source. From the literature, root-mean-square (RMS) limits were found to be more appropriate for avoiding disturbance, while Peak and Cumulative Sound Exposure Levels (cSEL) were found to be preferred for avoiding injury and death.

Table 1: Underwater Noise Criteria Limits

Type of Impact Concern	**Underwater Noise Criteria Limits 20 Hz to 10,000 Hz at a distance of 10 m (33 ft)**	
	Atlantic Sturgeon	**Sea Turtles**
Behavior Disturbance	150 dB RMS re: 1 µPa	166 dB RMS re: 1 µPa
Injury or Death	206 dB Peak re: 1µPa or 187 dB cSEL re: 1µPa^2•sec	N/A

The contractor was also required to deploy three forms of mitigation, a pile cap cushion, an underwater bubble curtain and a turbidity barrier. Pile cap cushions made of nylon, rubber, plastic, wood, or other acceptable material are placed on top of the pile to eliminate the metal-on-metal contact during impact pile driving. A bubble curtain forms a vertical layer of air bubbles which acts as an acoustical impedance mismatch through it and the water column, thus reducing noise propagation efficiency. A turbidity barrier is a solid fabric or vinyl sheet hung from floats which serves to reduce wave action to some degree, contain particulate matter, and act as a physical barrier to keep fish and turtles at a safe distance from the construction operations.

In addition, the contractor was required to submit an Underwater Noise Control Plan for approval before work could commence. The plan would need to demonstrate the contractor's understanding of the specification, describe the intended work schedule and equipment locations, and provide specific means and methods to comply with the noise criteria limits.

4. INSTRUMENTATION

The underwater noise instrumentation used to monitor contractor compliance on this project had to be selected very carefully due to the requirements in the specification and available staff to perform the assignment. In this case, field inspectors would periodically collect underwater noise data and then send it to acoustical experts for review, data reduction and determination. Thus, a relatively simple-to-use underwater noise data measurement and recording system needed to be configured for the field inspectors. The system had to be capable of acquiring and recording uncompressed waveform audio files (.wav) of the underwater construction noise which were then transmitted electronically to the acoustical experts for analysis. This data collection and analysis approach worked very well in practice.

As shown in Photo 2, the transducers selected for this project were RESON TC-4033 hydrophones of nominal sensitivity -203 dB re: 1V/µPa (0.07 mV/Pa). The hydrophones had 20 meter (66 feet) integral cables, however water depth was not an issue on this project as the bay is only a few meters deep at any location. Being a charge device, the hydrophone's signal was first passed through a Brüel & Kjær 2635 charge amplifier so that it could be conditioned, filtered and amplified if needed. Then the AC signal was passed to a RION DA-20 data recorder to produce a waveform file in the field.

Photo 2. Underwater Noise Instrumentation

The waveform files and associated field notes were then sent to acoustical experts for data reduction and analysis. A SINUS SoundBook analyzer was used for this purpose. The data was analyzed in broadband and third-octave bands from 20 Hz to 10,000 Hz using the noise metrics of RMS Lmax to evaluate the disturbance criterion and Peak and RMS cSEL to evaluate the injury/death criterion. The entire system was calibrated beforehand and periodically thereafter using a GRAS 42AC pistonphone calibrator with a BRC RA-0078 hydrophone adaptor. Using this instrumentation and data collection method, the important system design considerations of very high dynamic range, low distortion, wide acoustic bandwidth, excellent frequency response, and robust components were solidly achieved.

5. DATA REDUCTION & FINDINGS

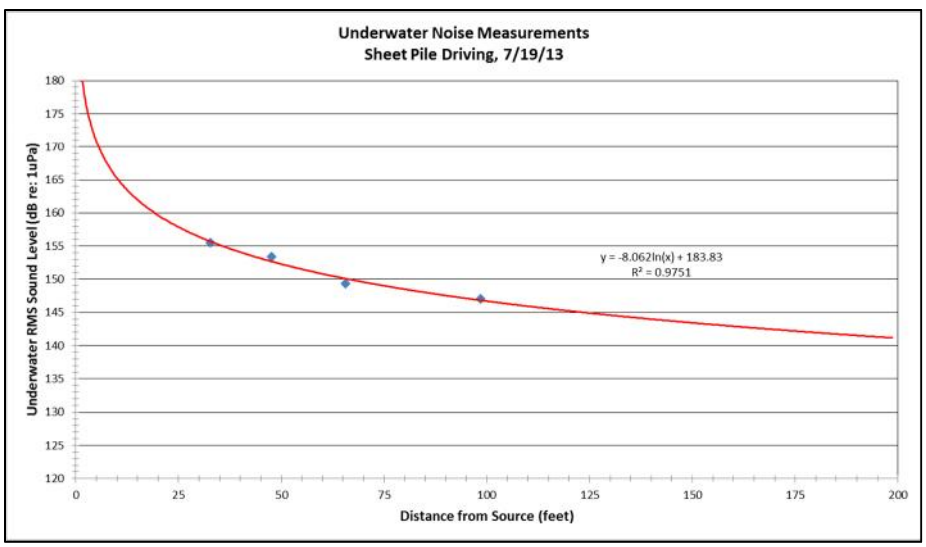
Underwater noise data has been collected periodically for pile driving and caisson drilling operations during this project's initial year of construction. The water depth in the bay is quite shallow (only a meter or two), so the hydrophone is typically positioned at a depth halfway between the surface and the bottom. Data was collected at various distances from the noise sources and on both sides of bubble curtains and turbidity barriers in order to allow for some noise trend and behavior analyses as well.

The noise drop-off rate for a vibratory pile driver working on steel sheet piles was measured in July 2013, as shown in Photo 3, with the results shown in Figure 1. In Log base 10 format, the measured underwater pile driver noise level as a function of distance could be described as ***dB re: 1uPa = -18.6 Log (feet) + 183.83***, which corresponds to a drop-off rate of slightly under 6 decibels per doubling of distance from the source. This drop-off rate is consistent with acoustical theory for a point source propagating into slightly less-than-ideal hemispherical far-field space.

Unfortunately, the bubble curtain could not be turned off to perform a proper insertion loss measurement, so its noise reduction was measured using two hydrophones at once; one on each side of the bubble curtain while the pile driver was operating. The results indicated that the bubble curtain was providing only 3 to 4 decibels of noise reduction; however greater reduction could be expected with more airflow through the system. Similar measurements on both sides of the turbidity curtain were inconclusive; however the turbidity curtain was not expected to provide a measurable noise reduction across it as its purpose is to act as a physical barrier to keep fish and turtles away from the area and contain particulates within the construction zone.

Photo 3. Vibratory Sheet Pile Driver

Figure 1: Underwater Noise Propagation from Sheet Pile Driving in Shallow Water



During the time this project has been active there have been hundreds of underwater noise data samples collected involving various construction methods, equipment and locations. The results are summarized in Table 2 for the unmitigated measurements performed at a reference distance of 10 meters (33 feet) from the noise-producing equipment. Three types of equipment have been sampled thus far: caisson drills, vibratory pile drivers and impact pile drivers. The results in Table 2 have been averaged over the number of samples available for each type of equipment and operation. The samples' high, low and mean values are provided. As the mean values indicate, unmitigated noise levels from vibratory and impact pile driving can exceed criteria intended to avoid behavior disturbance, however none of the equipment's average values exceeded the project's criteria for injury or death of these particular aquatic species.

Table 2: Underwater Noise Measurement Summary

Source Equipment	**Operation**	**Data Range**	**Underwater Noise Measurements (Unmitigated) 20 Hz to 10,000 Hz at a distance of 10 m (33 ft) in shallow water 1-2 m (3-6 ft) depth**		
			RMS Lmax dB re: 1µPa	**Peak dB re: 1µPa**	**cSEL dB re: 1µPa2•sec**
Caisson Drill	w/Digger Bucket	High	149	175	166
		Avg	**142**	**162**	**158**
		Low	135	150	151
Caisson Drill	w/Auger Bit	High	145	168	171
		Avg	**141**	**160**	**165**
		Low	135	151	143
Vibratory Pile Driver	Steel Sheet Piles	High	177	200	188
		Avg	**160**	**177**	**175**
		Low	145	159	161
Vibratory Pile Driver	Other Steel Piles*	High	171	198	181
		Avg	**158**	**178**	**169**
		Low	145	159	155
Impact Pile Driver	Other Steel Piles*	High	197	214	209
		Avg	**170**	**202**	**185**
		Low	159	189	174

(*) Excluding sheet piles

6. DISCUSSION OF CUMULATIVE SEL (cSEL)

During the literature review and formulation stage of this project, it became clear that the definition of Cumulative Sound Exposure Level (cSEL) was anything but clear. The "SEL" term was easily understood as being the energy-averaged decibel level that would have been produced had the entire "event" occurred in just one second. However, there was not good agreement over the use of the "cumulative" term, particularly with respect to the timeframe in question.

Some publications tried to calculate the cSEL as the SEL of a single impact pile strike plus 10 Log (total number of pile strikes). However, this appeared to be done because the measurement method used on some projects only examined a single pile strike impulse signal, and thus an estimate of noise produced while driving the entire pile was needed. In contrast, other publications described a much longer time period of concern when computing the cSEL. There was discussion of the longer-term adverse noise dose effects from ongoing construction, and the overnight recovery time required for aquatic species. Thus, this project decided to define the cSEL as the sound exposure level over the entire work shift of a given day. Reasons supporting this decision include (text in *italics* added for emphasis):

- The underwater noise data collection system used in this project was able measure noise continuously over an "event" of any duration, and thus was not restricted to just single pile strike impulses signals.
- The general purpose of the SEL metric in acoustics is to compare the total acoustical energy of an event of varying time durations. In that regard, SEL is a noise *dose* descriptor.
- The cSEL emphasizes the word "cumulative", also seen in the literature as "accumulated", meaning it is an SEL over some *extended* time period.
- This project already had a short-term noise criterion to define danger levels, i.e. 206 dB Peak, so defining the cSEL over just one pile seemed redundant for its intended purpose.
- A free downloadable underwater noise calculation spreadsheet produced by the National Marine Fisheries Service (NMFS) indicated the following: "Currently there are no data to support a tissue recovery allowance between pile strikes. *Therefore, all strikes in any given day are counted, regardless of time between strikes.* However, generally the accumulated SEL can be reset to zero overnight (*or after a 12 hour period*), especially in a river or tidally-influenced waterway when the fish should be moving."
- In several references reviewed, the cSEL level was well below the RMS level (by 10 dB or so), indicating that the cSEL had to be accounting for long periods of down time when pile driving was not occurring. This was true for vibratory driving as well as impact driving.
- From ITAP Institut für technische und angewandte Physik GmbH: "For evaluating the biological impact of pile driving in terms of a noise dose, it may be reasonable to consider not only the strength of a single strike, but to define the SEL "event" as a series of strikes (*up to the whole pile driving process*, which may take several thousand strikes)."
- From the Oregon LNG Terminal and Oregon Pipeline Project: "The number of strikes included in the cumulative SEL is based on a summation period. Typically, *the summation period is one day* and includes a break in pile driving of at least 12 hours."
- And from NCHRP 25-28, there were instructions to: "Calculate the cSEL value for the number of pile strikes to be done *for that day*."

7. CONCLUSIONS

An underwater noise control program was developed and implemented for a major Mid-Atlantic bridge construction project in order to avoid adversely impacting or harming Atlantic sturgeon and sea turtles. The program included an underwater noise specification, mandatory noise mitigation measures, a noise monitoring system, and compliance reporting. The project has been underway for nearly a year and the underwater noise program appears to be working effectively.

Challenges encountered during the process included (1) developing a meaningful underwater noise specification, (2) defining and adopting appropriate noise criteria limits, particularly the cSEL, (3) configuring a suitable underwater noise monitoring system, and (4) training inexperienced field staff to collect noise data under occasionally difficult circumstances.

Excessive construction noise can clearly impact more than just human beings within close proximity of the project. It is hoped that control of underwater noise becomes a standard concern for all major "marine zone" construction projects, and that additional analysis tools, criteria and guidance can be developed to better standardize the process for protection of aquatic species.

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