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Protecting aquarium sea mammals and fish from pile driving noise and vibration

Erich Thalheimer
WSP USA, Inc.
100 Summer Street
Boston, MA 02110
Erich.Thalheimer@WSP.com

Brian Isoldi
WSP USA, Inc.
One Penn Plaza
New York, NY 10119
Brian.Isoldi@WSP.com

Edward Tadross
WSP USA, Inc.
One Penn Plaza
New York, NY 10119
Edward.Tadross@WSP.com

ABSTRACT

Marine mammals and fish on exhibit at the Maritime Aquarium in Norwalk, Connecticut were the subject of an extensive study to predict, assess, measure and control pile driving noise and vibration levels produced by construction activities associated with an upcoming major railroad bridge replacement project proximal to the aquarium. There was great concern that the aquarium's harbor seals, sea turtles and various fish species could be adversely affected or even harmed by stress from the pile driving. This paper will describe the development of relevant criteria limits, prediction of pile driver noise and vibration levels, and most importantly, the extensive measurements that were performed during a live pile driver test program conducted in late-2018. Air-borne noise, ground-borne vibration and hydro-acoustic levels were measured in real-time as test pile driving was conducted at nine locations using three different types of pile drivers. The results proved successful in protecting the aquarium's sensitive species of concern, and the resulting study reassured the Federal Railroad Administration (FRA), Connecticut Department of Transportation (CTDOT) regulators, project designers and aquarium management that the bridge replacement project could be conducted safely.

1 INTRODUCTION

The Walk Bridge Replacement Project will restore the existing deteriorating rail bridge over the Norwalk River in Norwalk, Connecticut. This bridge is a key link for the Northeast Corridor (NEC) Amtrak route between New York and Boston. The Maritime Aquarium (**Photo 1**) is directly adjacent to the Walk Bridge along the Norwalk River. As part of the Walk Bridge Replacement Project, and in order to address concerns about construction adversely affecting the Maritime Aquarium's various species, noise, vibration and hydro-acoustic monitoring was performed at the aquarium building for its fish and sea mammal species during a test pile driving program (TPP) in late-2018.

Photo 1: Maritime Aquarium, Norwalk, CT

Hydro-acoustic levels inside the 'Seal Tank' and the 'Go Fish Tank', as well as noise and vibration levels exterior to the aquarium building, were monitored during all TPP activities in accordance with the methodology and criteria limits described in the protocol developed for the project - *Maritime Aquarium Final Test Pile Program Noise, Vibration and Hydro-Acoustic Monitoring Protocol* (i.e. Protocol). The Protocol described the measurement instrumentation, techniques, criteria limit thresholds, and steps that would be taken in the event noise and/or vibration levels exceed agreed-upon alert thresholds during TPP activities.

A comprehensive communication system was established to keep all parties informed as the test pile rig was moved between the nine test sites in the river and as different pile drivers were used. All piles were driven to design depth using either a hydraulic impact, diesel impact or vibratory pile driver and then removed while noise, vibration and hydro-acoustic levels were monitored at the aquarium. The pile driving could be stopped if noise or vibration levels exceeded allowable limits or if the aquarium's marine biologists determined the animals or fish were behaving oddly.

2 BASELINE MONITORING AND CRITERIA

2.1 Baseline Levels

Baseline noise, vibration and hydro-acoustic levels were measured throughout the Maritime Aquarium for a week in August 2017. In this manner, noise, vibration and hydro-acoustic levels measured during the TPP could be directly compared against those that were measured during the baseline data collection exercise. Irrespective of the noise, vibration and hydro-acoustic criteria limits selected for this project, these baseline levels were important to note because the harbor seals, sea turtles and fish in the Go Fish Tank residing in the aquarium were in good health when exposed to the existing conditions. Thus, the baseline levels helped put any future measured levels into better perspective.

2.2 Criteria Limits

The criteria limits that were established in the Protocol are shown here in **Table 1**. **Figure 1** shows the aquarium noise, vibration, and hydro-acoustic monitoring locations during the TPP. Hydro-acoustic monitoring consisted of 1-minute samples in the Seal Tank to ensure that hydro-acoustic levels would not exceed 160 dB Lmax 'slow' (representing potential disturbance) or 200 dB Peak (representing potential injury). Similarly, 1-minute hydro-acoustic samples were monitored in the Go Fish Tank to ensure hydro-acoustic levels did not exceed 150 dB Leq 'slow' (disturbance) or 206 dB Peak (injury). These hydro-acoustic criteria where adopted from ANSI/ASA S3/SC1.4 TR-2014 Sound Exposure Guidelines for Fishes and Sea Turtles[(1)], and guidelines from the National Oceanic and Atmospheric Administration (NOAA)[(2)], the U.S. Fish and Wildlife Service (USFWS) and the National Marine Fisheries Service (NMFS)[(3)].

Vibration criteria for this project were established for avoidance of human annoyance as well as protection of the aquarium building itself. A human annoyance limit from ground-borne vibration of 75 VdB Lmax 'slow' was selected from Federal Transit Administration (FTA)[(4)] guidelines which assumes an institutional land-use category exposed to "frequent" vibration events. For the building, vertical Peak Particle Velocity (PPV) values of 0.500 inches/second and 0.200 inches/second were selected as limits for transient (e.g. impact pile driving) and continuous (e.g. vibratory pile driving), respectively.

Noise criteria for the exterior of the building were established in accordance with Federal Highway Administration (FHWA)[(5)] guidelines to avoid human annoyance from construction noise. A noise limit of 90 dBA Lmax 'slow' was selected for impulsive-type transient noise events, and a 20-minute limit of 80 dBA L10 'slow' was selected for continuous construction noise.

Table 1: Aquarium criteria limits for test pile program

Site No.	Aquarium Location	Interior or Exterior	Monitored Parameter	Affected Receiver[4]	Criteria Limits	
N-1	Riverside Courtyard Near Walk Bridge	Exterior	Air-borne Noise[1]	Human Annoyance	DAYTIME (7 AM to 6 PM) 90 dBA Lmax (transient) 80 dBA L10 (continuous)	
V-1	Riverside Courtyard Near Go Fish Tent	Exterior	Ground-borne Vibration[2]	Human Annoyance[6]	75 VdB Lmax (transient)	
				Building Damage	0.500 inch/sec PPV (transient) 0.200 inch/sec PPV (continuous)	
H-1 H-2 H-3	Go Fish, Harbor Seal, and Sea Turtle Tanks	Interior	Hydro-Acoustic[3]	Harbor Seals (H-2)	Disturbance 120 dB Leq 160 dB Lmax	Injury 190 dB Lmax 200 dB Peak
				Sea Turtles (H-3)	Disturbance 166 dB Leq	Injury 207 dB Peak 210 dB SELcum
				Go Fish Tank (H-1)	Disturbance 150 dB Leq	Injury 206 dB Peak 187 dB SELcum

Notes: (1) Air-borne noise decibels referenced to 20 µPa.
(2) Ground-borne vibration velocity decibels referenced to 1 µ-inch/second.
(3) Hydro-acoustic decibels referenced to 1 µPa.
(4) Due to the unavailability of published research on noise/vibration effects, Meerkats and Reptiles will be monitored solely by Maritime Aquarium staff for signs of stress.
(5) Maritime Aquarium staff will also monitor behavior of Harbor Seals, Sea Turtles and Fish. If noise/vibration levels are below criteria limits but Aquarium staff observe signs of unacceptable stress, test pile work will be stopped and mitigated.
(6) The "Human Annoyance" vibration level for Site No. V-1 is based on a Land-Use Category 3 building type with a "Frequent Events" frequency, defined as more than 70 vibration events per day.

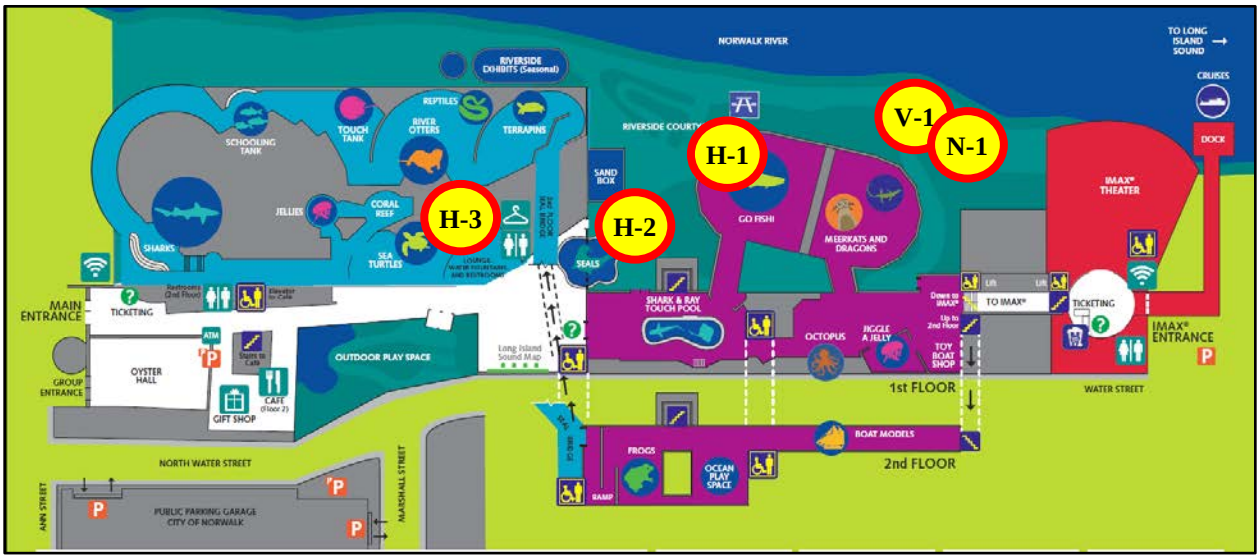

Figure 1: Aquarium noise, vibration, and hydro-acoustic monitoring locations

3 TEST PILE PROGRAM

3.1 Hydro-Acoustic Equipment

Hydro-acoustic levels were measured using Reson Model TC4033 hydrophones, powered by Bruel & Kjaer Model 2635 charge amplifiers, streaming their data into a Sinus SoundBook for analysis and recording. The system was calibrated with a GRAS Model 42AC calibrator and BRC Model RA0078 hydrophone coupler. Pictures of the hydrophones in the Go Fish Tank and Seal Tank and the hydro-acoustic data collection system can be seen in **Photos 2 – 5**.

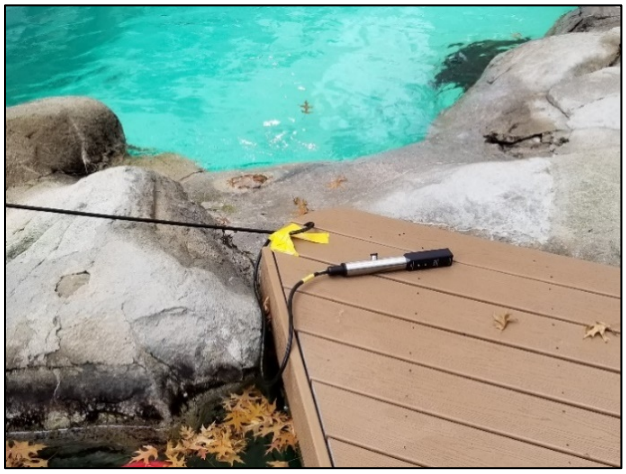

Photo 2: Hydrophone and calibrator in seal tank

Photo 3: Hydrophone immersed in seal tank

Photo 4: The go fish tank

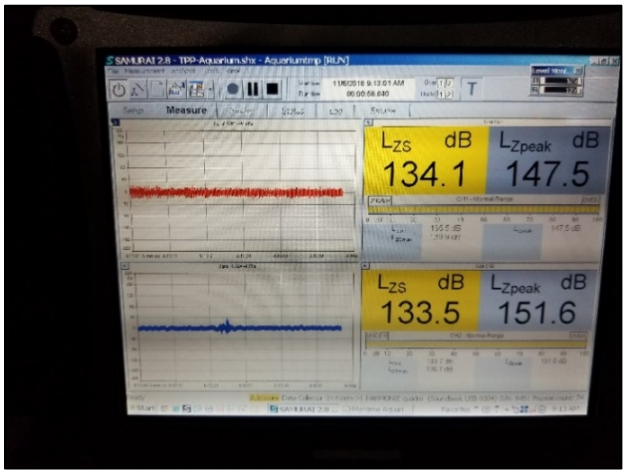

Photo 5: SoundBook analyzer data stream

3.2 Noise and Vibration Equipment

Exterior noise and vibration levels were measured using a Bruel & Kjaer EMS Model 3655-C Noise Sentinel and a Model 3680-B Vibration Sentinel automated monitoring systems. The monitors were positioned behind the aquarium on pavement at the southeast corner of the property closest to the rail bridge. The Sentinels monitor noise and vibration levels on a continuous basis (24/7), upload the data to a host server in real-time, and send out automated alert messages in the event noise or vibration levels start to exceed specified thresholds. Pictures of the noise and vibration Sentinel systems can be seen in **Photos 6 – 7**.

Photo 6: B&K EMS Sentinel automated monitors

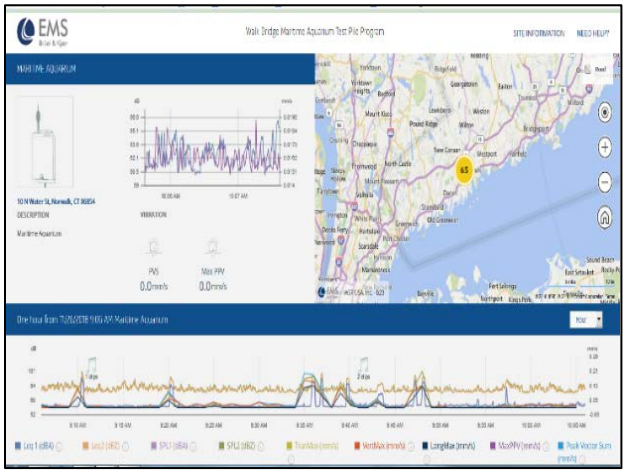

Photo 7: B&K EMS Sentinel data website

3.3 Monitoring Details

Sheet and cylinder piles were driven and pulled by the contractor at a total of nine test sites in the river using four different pile driving rigs. The program started with the test pile location farthest away from the aquarium (approximately 850 feet) on November 6th, 2018 and continued for twelve working days through the test pile location closest to the aquarium (approximately 100 feet) on November 28th, 2018. Hydro-acoustic levels inside the Seal Tank and the Go Fish Tank, and noise and vibration levels exterior to the aquarium building, were monitored during all TPP activities in accordance with the Protocol.

While noise and vibration levels were monitored from the perspective of human annoyance, only the hydro-acoustic levels in the water tanks affecting the seals and fish, and vibration levels that could potentially damage the building itself, were actively scrutinized for potentially halting TPP work if the levels exceeded allowable limits. Aquarium biologists could also halt the tests at any time due to any observed erratic species behavior of concern.

Hydro-acoustic monitoring was performed during all TPP-related activities as well as during some periods without pile driving. Noise and vibration monitoring was performed continuously during the workday (8 AM to 6 PM). Monitoring times were extended beyond pile driving intervals in order to characterize the background noise, vibration and hydro-acoustics levels. In some cases, background levels were found to be greater than the levels monitored during pile driving due to other non-TPP-related events.

A total of four pile drivers were used during the TPP including an ICE Model 28D and an APE Model 200 vibratory driver, a Berminghamer Model B64 diesel impact hammer, and a Junttan Model HHK 5/7S hydraulic impact hammer. Piles consisted of both steel sheet piles and hollow steel caisson piles. All test piles were driven to completion and pulled out afterwards.

4 TPP MONITORING RESULTS

The results of the TPP monitoring program performed at the Maritime Aquarium are summarized in **Table 2**. Maximum levels presented in the table may or may not have been caused by the pile driving, but TPP activities were occurring at the time of these measurements.

As shown in the table, measured levels remained well within established hydro-acoustic criteria to avoid disturbance and injury to the monitored species (seals and fish), and building vibration levels remained well below criteria for possible damage to the building itself. Therefore, TPP work did not need to be interrupted to protect the aquarium building or its specimens.

As can also be seen in the table, vibration levels remained below the criteria limit for human annoyance, however the noise levels measured outside the building often exceeded the selected limits. Again, only the hydro-acoustic levels and the building damage vibration levels could have stopped the TPP. Exceeding the human annoyance thresholds for noise or vibration would not have stopped the TPP. However, project managers will clearly have to do more work towards addressing and mitigating the noise levels that will be generated during the actual project.

Representative results are also shown graphically in **Figures 2 – 4** for hydro-acoustics, noise and vibration, respectively. As shown, none of the critical monitored levels exceeded their limits. The yellow highlighted areas in the figures identify when work was stopped due to non-TPP-related fish behavior (which turned out to be food related). Thus, the monitored data was important to show lack of TPP impact during this odd fish behavioral event.

Table 2: Summary of maximum aquarium TPP hydro-acoustic, noise and vibration levels

Date	TPP Pile	Hydro-Acoustic				Vibration			Noise	
		Go Fish Tank		Seal Tank		Human Annoy-ance	Building Damage		Human Annoyance	
		Disturb	Injure	Disturb	Injure		Trans	Cont	Trans	Cont
Criteria Limit		**150 dB Leq**	**206 dB Peak**	**160 dB Lmax**	**200 dB Peak**	**75 VdB**	**0.500 PPV**	**0.200 PPV**	**90 dBA Lmax**	**80 dBA L10**
11/6/18	1	147	158	150	173	60	0.005	0.010	99	75
11/7/18	2	144	166	143	160	60	0.006	0.002	96	79
11/8/18	2 & 3	144	178	147	164	61	0.009	0.006	101	76
11/9/18	3 & 4	138	161	150	168	61	0.006	0.008	101	78
11/13/18	4 & 5	136	155	145	157	61	0.008	0.003	99	91
11/14/18	5	137	155	146	161	55	0.000	0.003	97	90
11/19/18	6	133	147	137	153	46	0.000	0.001	93	72
11/20/18	6	149	181	144	160	64	0.007	0.009	102	84
11/21/18	6	140	152	153	161	64	0.000	0.007	101	87
11/26/18	7	143	153	148	164	58	0.000	0.005	99	74
11/27/18	7 & 8N	143	157	157	166	63	0.014	0.009	100	89
11/28/18	8N & 9S	143	168	145	164	71	0.020	0.011	100	95

Note: Results shown in red exceed related applicable criteria limits.

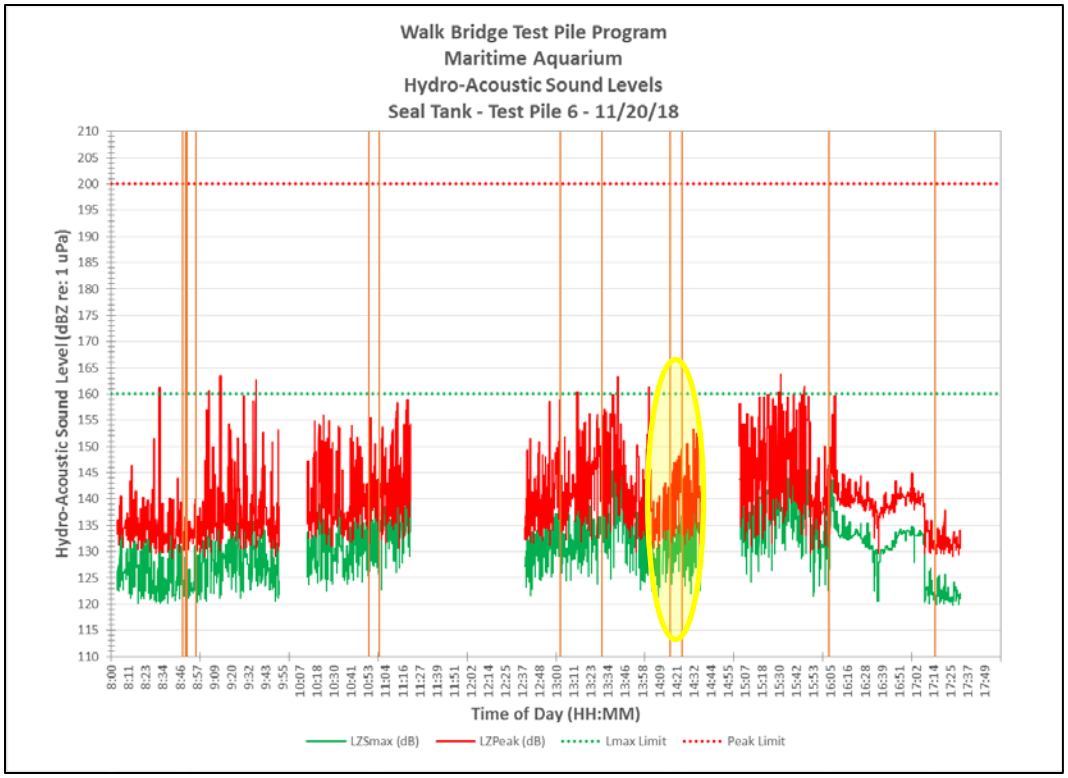

Figure 2: TPP hydro-acoustic monitoring results (Example)

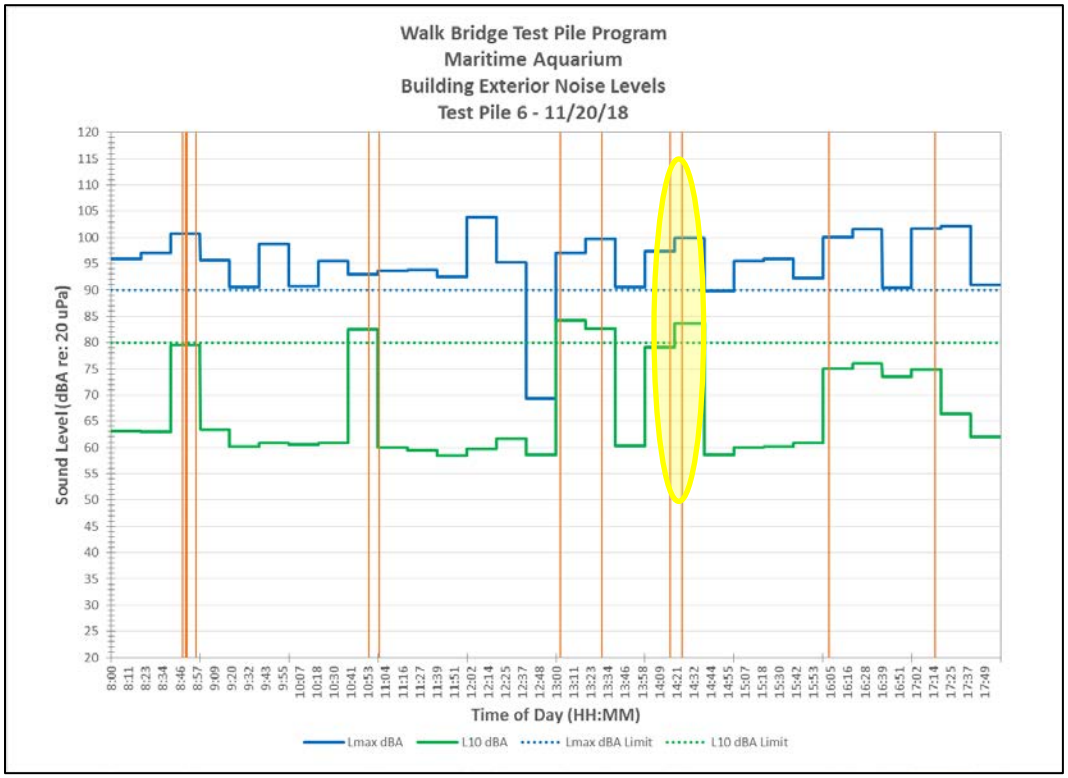

Figure 3: TPP noise monitoring results (Example)

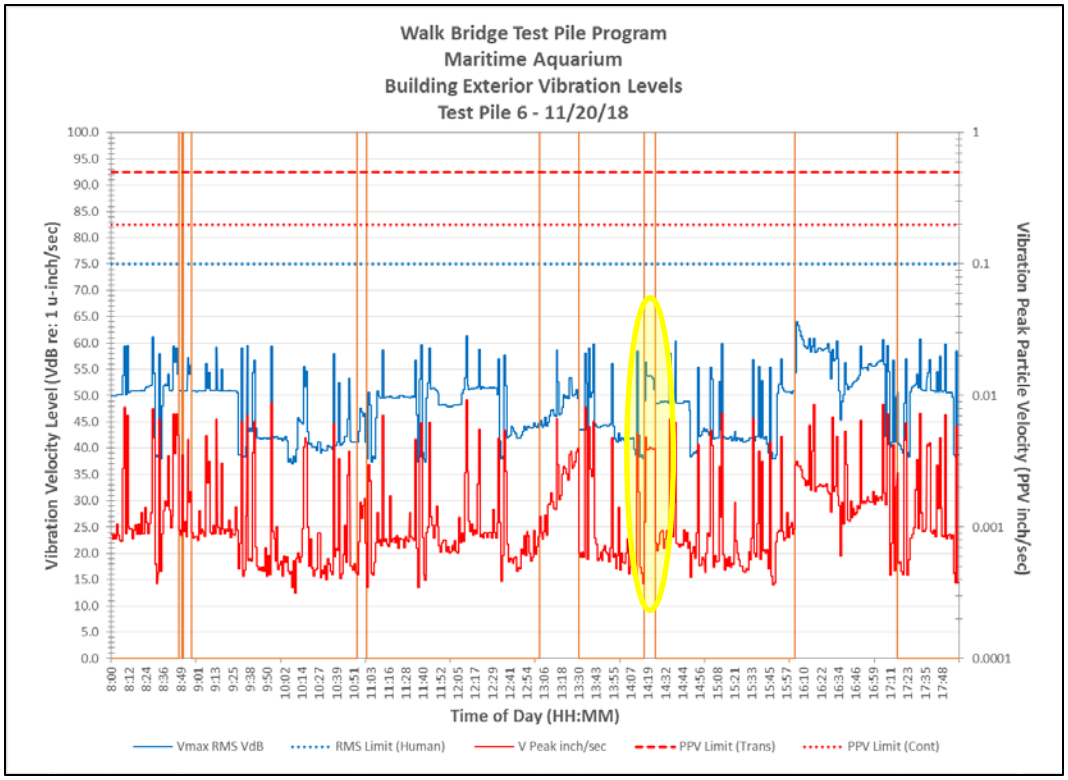

Figure 4: TPP vibration monitoring results (Example)

5 CONCLUDING COMMENTS

Hydro-acoustic, noise and vibration levels at the Maritime Aquarium were successfully monitored during the Walk Bridge Project's Test Pile Program. The results yielded valuable information regarding the potential vulnerability and susceptibility of the aquarium, its seals, and its fish species with respect to construction-induced impacts. The TPP was intended to assess the likelihood of such impacts and to determine if mitigation measures would be needed during the project's construction phase, which could last up to three years.

To the great relief of aquarium management, FRA and CTDOT, monitored hydro-acoustic levels inside the Seal Tank and Go Fish Tank remained well below applicable limits for avoiding disturbance or injury to the fish or marine animals. Furthermore, monitored building vibration levels were also well below the criteria for potential building damage, and remained below the limit for human annoyance to vibration as well. However, TPP-related noise levels were often found to exceed the outdoor noise limits; a concern that will need to be addressed further before the full project commences. Consequently, a similar monitoring program will be implemented during the actual bridge replacement project, and aquarium staff will work cooperatively with FRA and CTDOT officials towards a common goal.

6 REFERENCES

1. *Sound Exposure Guidelines for Fishes and Sea Turtles*, ANSI/ASA S3/SC1.4 TR-2014, (Acoustical Society of America, 2014).
2. *NOAA Effects of Anthropogenic Noise on Marine Mammal Hearing*, (National Oceanic and Atmospheric Administration, 2016).
3. Anthony D. Hawkins and Arthur N. Popper, "Assessing the impact of underwater sounds on fishes and other forms of Marine life", *Acoustics Today*, (2014).
4. *FTA Transit Noise and Vibration Impact Assessment Manual*, U.S. Department of Transportation, (Federal Transit Administration, 2018).
5. *FHWA Highway Construction Noise Handbook*, U.S. Department of Transportation, (Federal Highway Administration, 2006).