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Forensic Evaluation of Construction Noise and Vibrations Associated with an Urban Drainage Project

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Abstract

This study performed a forensic evaluation of construction noise and ground vibration propagation to surrounding residential and commercial structures as a result of an urban drainage improvement construction project. Noise and vibration data collected during the course of the drainage project was first evaluated for conformance with the project specifications and data collection protocols. Construction equipment utilization logs were used to create a "time history" of daily maximum noise levels, which were contrasted with the maximum allowable per the project specifications. Attenuation relationships were used to delineate ground vibration extents and magnitudes propagating from the source to adjacent receptors (i.e., structures). The forensic engineer (FE) found significant deviations from the required data collection protocols and a high degree of "under-reporting." Construction-induced noise and ground vibrations were determined to be "substantial factors of harm" to the adjacent structures.

Keywords

Construction dispute, construction noise, construction vibrations, drainage culverts, historic district, loss of use, noise monitoring, structural damage, vibration monitoring, residential impacts, urban construction, forensic engineering

Overview

A lawsuit was filed by residents situated adjacent to a major urban drainage improvement construction project in a historic district against the utility owner (utility) for damages including physical distress and loss of use as a result of the construction activities. The intent of the drainage improvement project was to minimize inundation associated with a 10-year recurrence interval precipitation event. The project entailed the construction of new, below-grade, drainage culverts to temporarily store and more rapidly convey stormwater to discharge points within the larger drainage network. The new culverts were installed primarily beneath a center median of a four-lane residential roadway, which resulted in partial closure and construction activities abutting residential properties.

The FE approach applied to this engagement consisted of the following steps:

- Perform a literature review of the standard of practice for noise and vibration damage;
- Review the project-specific construction bid package (plans and specifications);
- Review the project-specific construction submittals and requests for information (RFIs);
- Review available construction documentation (daily field reports, photographs, etc.) during the course of the work; and
- Analyze impacts relative to the litigation claims.

For this engagement, the determination of specific structural damage was the responsibility of another expert team. The role of the author, for this case, was to evaluate if the construction-induced construction noise and ground vibrations were "a substantial contributing factor" to the realized damages.

Summary of the State of the Practice — Noise

A number of sources provide insights as to impacts of noise[1,2,3,4,5,6,7,8,9,10,11,12]. Construction activities, much like highways, generate noise or "unwanted sound"[12]. The Federal Transit Administration (FTA) notes that[12]:

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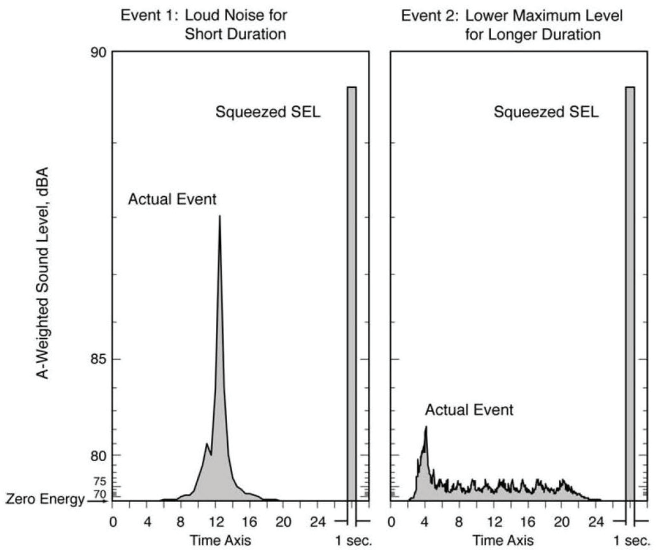


Figure 1
Sound energy is a cumulative phenomenon where short-duration loud noises can have similar sound energy as longer duration low noise[12].

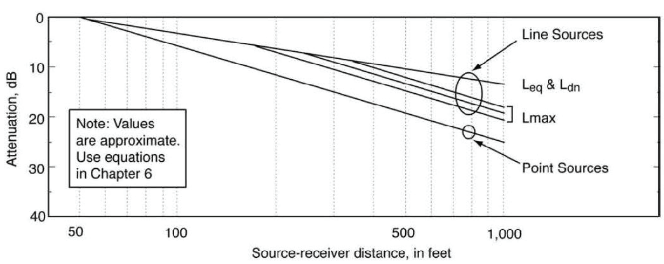


Figure 2
Example attenuation due to distance between source and receiver[12].

Noise is generally considered to be unwanted sound. Sound is what we hear when our ears are exposed to small pressure fluctuations in the air. There are many ways in which pressure fluctuations are generated, but typically they are caused by vibrating movement of a solid object. This manual uses the terms "noise" and "sound" interchangeably, since there is no physical difference between them. Noise can be described in terms of three variables: amplitude (loud or soft); frequency (pitch); and time pattern (variability).

The FTA[12] notes that the Sound Exposure Level (SEL) is a quantitative measure of the noise exposure for single noise events. The SEL is a cumulative measure (**Figure 1**), which means that louder events have a greater SEL than quieter ones, and vents that last longer in time have a greater SEL than shorter ones. FTA notes that "people react to the duration of noise events, judging longer events to be more annoying than shorter ones." When two or more combinations of sound pressure sources exist, the sound energies are added for an increase in overall sound level. For example, doubling identical sound sources (such as

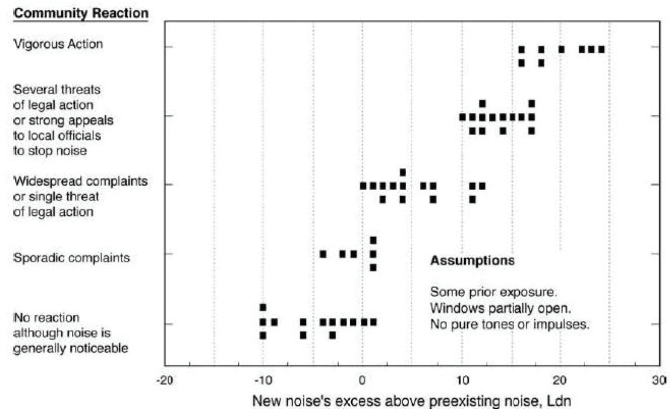


Figure 3
Community reaction to elevated noise levels[12].

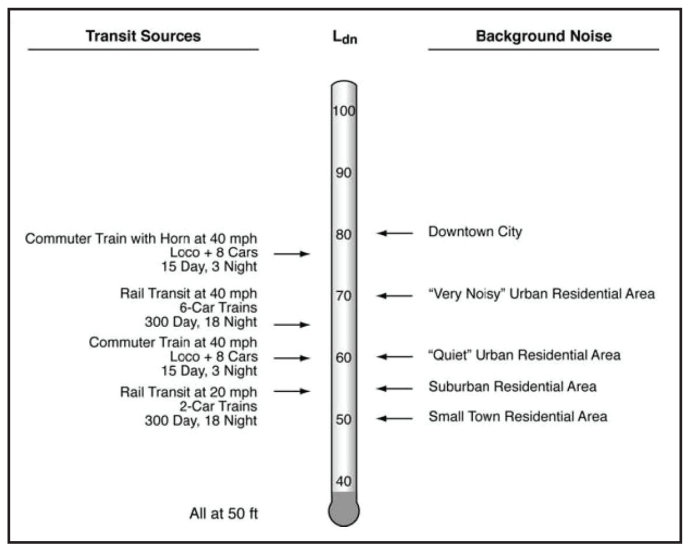


Figure 4
Typical background noise levels[12].

two jackhammers operating at once) result in a 3dB increase. Sound levels decay with distance. Typical attenuation relationships are shown in **Figure 2**.

Increased noise level has been documented to generate response from exposed communities (**Figure 3**). Typical background noise levels for urban residential areas is on the order of 60dB (**Figure 4**). **Figure 5** shows typical background noise levels for various conditions. Typical noise ranges for various construction equipment are presented in **Figure 6** and **Figure 7**.

Summary of the State of the Practice — Vibrations

Guidance exists on impacts to structures from construction vibrations[13,14,15,16,17,18,19,20,21,22]. These reports identify the challenges associated with correlating vibration damage to structural damage. Structure response to ground vibrations depend on many factors, such as the soil conditions, structure foundation type, structure mass, and structure stiffness[13]. For example, wood and steel are more elastic materials than brick and stone. As a result, wood and steel may be more resistant to ground vibrations[13]. NCHRP 25-25 (Task 72) notes that "[t]he condition of a building and its maintenance are important factors when assessing susceptibility to vibration damage and must be taken into account when setting vibration limits"[13]. In addition, shaking effects of construction-generated ground vibrations can cause ground settlement or shifting that significantly reduces support provided by the soil, causing damage to the structure(s)[13,23,24,25,26].

Sound	dBA
Thunderclap	120
Thunder	110
Stream, water flowing	73
Surf, pounding	70
Wind, breeze through trees	62
Birds, singing	60
Wind, gusty with rustling tree foliage	55
Rainfall, moderate	50
Rainfall, light	40
Rustling leaves	40
Olympic National Forest	40
Mountaintop	35
Wilderness ambient	35
Lake, quiet	30
Meadow, low wind conditions	30
Insects	25
Mountain slope, open	23
Rustling leaves	20
Grand Canyon, remote trail	15
Grand Canyon at night	10
Haleakala volcano crater, no wind	5

Source: Federal Highway Administration 2011.
dBA = A-weighted decibels

Figure 5
Background noise levels for various conditions[10].

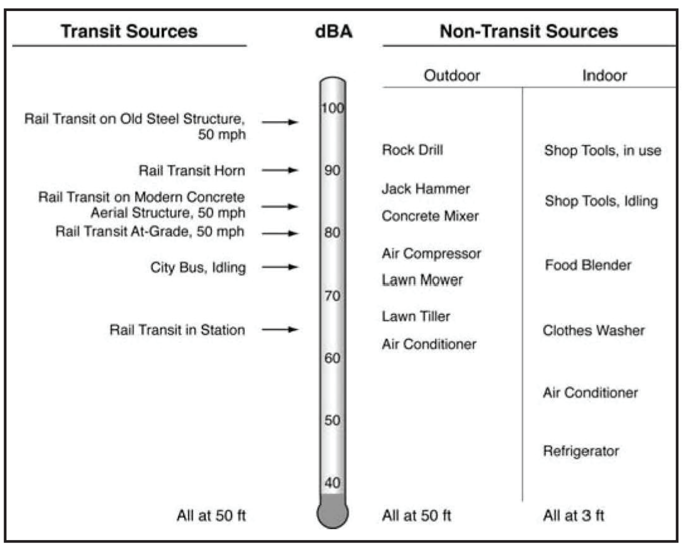


Figure 6
Typical sound levels[13].

For continuous vibrations such as vibratory compaction and vibratory pile driving, NCHRP 25-25 Task 72 suggests[13] the following thresholds for "Peak Particle Velocity" or PPV:

- PPV that exceeds 0.035 in./second is generally considered to be distinctly perceptible;
- PPV of 0.10 in./second would be strongly perceptible and begins to annoy;
- PPV of 0.2 in./second is definitely annoying;
- PPV between 0.4 and 0.6 in./second would be unpleasant.

Figure 8 shows typical peak particle velocity (PPV) ranges/responses and typical vibration sources. Impact pile driving and vibratory pile driving typically have PPVs on the order of 0.8 to 1.0 in./second at a distance of 25 ft from the source. **Figure 9** shows typical vibration source levels for construction equipment[13]. The Federal Transit Agency[13] offers a formula to estimate vibration attenuation based on distances greater than 25 ft from the source (**Figure 10**). This simplistic formula is based on distance, the reference PPV, and an adjustment factor based on "competent" soil and "hard" soil. A minimum

(Colors indicate relative sound level: red = extreme, orange = very high; yellow = high; green = moderate; blue = low; purple = very low; mauve = background. Asterisks show impact noise sources.)

	Noise (dBA)		
	Low	High	Impact[a]
Explosives	94	162	*
Rock Blast	112	112	*
Pneumatic Tools, Jackhammers & Pile Driver	101	110	*
Track Hoe	91	106	*
Impact Pile Driver	96	106	*
Guardrail Installation and Pile Driving	95	105	*
Truck Horn	104	104	*
Pile Driving	74	103	*
Rock Drill and Diesel Generator	80	99	
Rock Drill	85	98	
Dump Truck	82	98	
Rock Drills and Jackhammers	82	97	*
Pneumatic Wrenches, Rock Drills	86	97	*
Vibratory (Sonic) Pile Driver	95	96	*
Diesel Truck	85	96	
Pneumatic Chipper	91	95	
Hydromulcher	87	94	
Clam Shovel	93	93	
Slurry Machine	82	91	
Pneumatic Riveter	91	91	
Circular Saw (hand held)	91	91	
Mounted Impact Hammer Hoe-Ram	85	90	
Concrete Saw	90	90	
Compressor	80	90	
Scraper	85	89	
Paver	80	89	
Large Truck	84	89	
Jackhammer	74	89	
Drill Rig	85	88	
Dozer	84	88	
Crane	85	88	
Pumps, Generators, Compressors	81	87	
Front-end Loader	80	87	
Large Diesel Engine	86	86	
Gradall	85	86	
Chain saws	75	86	
Road Grader	83	85	

	Noise (dBA)		
	Low	High	Impact[a]
Pump	77	85	
Impact Wrench	85	85	*
Concrete Truck	81	85	
Concrete Mixer	80	85	
Auger Drill Rig	85	85	
Flat Bed Truck	84	84	
Backhoe	80	84	
Generator	52	84	
Ground Compactor	80	82	
Concrete Pump	82	82	
Cat Skidder	81	81	
Roller	74	80	
Horizontal Boring Hydraulic Jack	80	80	
Concrete Vibrator	76	76	
Welder	73	73	
Pickup Truck	55	71	
Yelling	70	70	
Background Sound Level—Forest Habitats	25	44	
Speech (normal)	41	41	

Source: U.S. Fish and Wildlife Service 2006.
a Impact noise = sudden, loud impulsive sound
dBA =A-weighted decibels

Figure 7
Noise ranges for various construction equipment[10].

screening distance of 500 ft is recommended[13]. NCHRP 25-25 notes that "vibration measured at ground level can sometimes be lower than vibrations inside the building due to amplification of vibration caused by resonances in building floors."

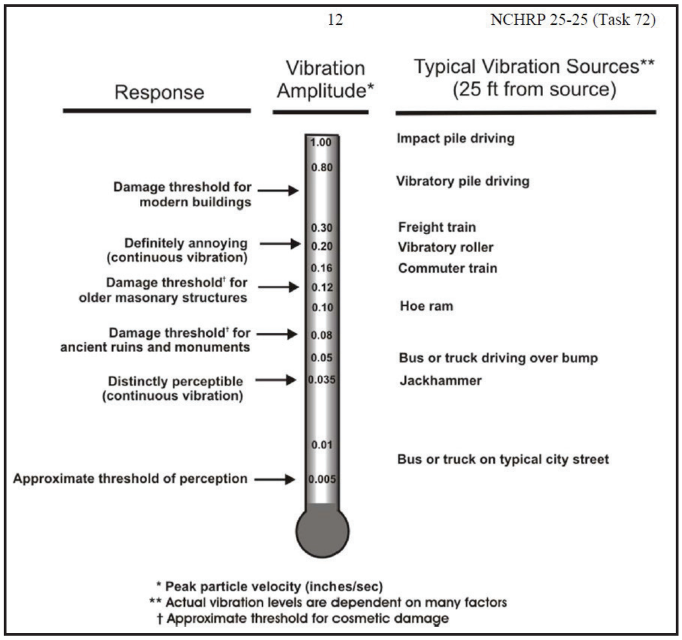


Figure 8
Vibration guidance from NCHRP 25-25 (Task 72)[13].

Vibration Source Levels for Construction Equipment

Equipment	PPV at 25 feet
Pile driver (impact)	0.644 to 1.518
Pile drive (sonic/vibratory)	0.170 to 0.734
Vibratory roller	0.210
Hoe ram	0.089
Large bulldozer	0.089
Caisson drilling	0.089
Loaded trucks	0.076
Jackhammer	0.035
Small bulldozer	0.003

Source: Federal Transit Administration 2006.

Figure 9
Table of vibration source levels for typical construction equipment[13].

$$PPV_{equip} = PPV_{ref} \text{ x } (25/D)^n$$

where: PPV (equip) is the peak particle velocity in in/sec of the equipment adjusted for distance

PPV (ref) is the reference vibration level in in/sec at 25 feet

D is the distance in feet from the equipment to the receiver

n is the attenuation exponent

n = 1.5 for *competent soils:* most sands, sandy clays, silty clays, gravel, silts, weathered rock (can dig with a shovel)

n = 1.1 for *hard soils:* dense compacted sand, dry consolidated clay, consolidated glacial till, some exposed rock (cannot dig with a shovel, need a pick to break up)

Figure 10
Adjustment equation for estimated vibrations at distances greater than 25 ft[13].

There is a wide range of opinion on appropriate vibration limits for structures. At one end of the spectrum is a limit of 0.10 in./second (except for ancient ruins/monuments where 0.08 in./second is thought to be appropriate) and at the other end of the spectrum, 0.5 in./second to 2.0 in./second are suggested.

Project Documentation — Noise

Documentation for the project generated during discovery was reviewed and included: the project plans and specifications; contractor submittals and RFIs; contractor daily field reports; and contractor photos. A review of the project specifications identified requirements for noise. The project specifications required the utility to contract with an independent company to monitor noise levels at the construction easement and notify the contractor of any exceedance instances. "Noise levels shall be limited to 85 decibels measured at the construction easement." Upon a review of the construction contracts, it became evident that no such independent company had been retained, and no monitoring occurred over the course of the project.

The contractor for the project maintained daily field logs noting the hour of operation of each type of equipment used on the project site each day as well as the number of hours the piece of equipment was in use (**Figure 11**). **Figure 12** presents a summary of the portfolio of equipment used during the course of the construction project.

CONTRACTORS QUALITY CONTROL REPORT (QCR)
DAILY LOG OF CONSTRUCTION

REPORT NUMBER 310 Page 2 of 2

DATE 27 Jul 2012 - Friday

PROJECT [redacted]

CONTRACT NUMBER [redacted]

QA/QC DEFICIENCY (Describe QC Deficiency items issued, Report QC and QA Deficiency items corrected)
No QC Deficiency items were issued today
No Deficiency items were corrected today

CONTRACTORS ON SITE (Report first and/or last day contractors were on site)
No contractors had their first or last day on site today

LABOR HOURS
The following labor hours were Reported today:

Employer	Labor Classification	Number of Employees	Hours Worked
[redacted]	FOREMAN	5.0	40.0
	LABORERS	14.0	80.0
	OPERATING ENGINEER	6.0	38.0
	QC PERSONNEL	1.0	8.0
	SAFETY ENGINEER - ON SITE	1.0	8.0
	SUPERINTENDENT	1.0	8.0
	SURVEYOR	2.0	16.0
	WELDER	2.0	14.0
Total hours worked to date:	7,099.0	Total 32.0	212.0

EQUIPMENT HOURS
The following equipment hours were Reported today:

Serial Number	Description	Idle Hours	Operating Hours
104.137	Air Compressor	0.00	8.00
191.309	Deere 310 puddle jumper	0.00	8.00
191.357	Deere 310 puddle jumper	0.00	8.00
191.428	Puddle Jumper	0.00	8.00
192.032	John Deere 134	0.00	8.00
192.048	CAT 312 Puddle jumper	0.00	8.00
192.056	CAT 312 Excavator	0.00	8.00
251.113	Deere Dozer	0.00	8.00
829313	Street Sweeper	0.00	8.00
r191112011	Cat 420 PJ Puddle Jumper	0.00	8.00
Total operating hours to date: 4,032.00		Total 0.00	80.00

Figure 11
Example contractor daily field report showing equipment used and number of hours. Source: Discovery Docs.

Equipment Description	Serial No.	Noise Type
185CFM Air Compressor	104.118	1
185CFM Air Compressor	104.137	1
210G LC John Deere Trackhoe	193.148	1
Air Compressor	104.137	1
Air Compressor	104.154	1
Air Compressor	108.760	1
Air Hammer	691.056	1
American 5299A Crane	224.016	1
American 5300 Crane	225.009	1
Blue Iron Silent Piler	BlueIron01	1
CAT 312C Trackhoe	192.046	1
CAT 329E Trackhoe	193.138	1
HP 915 Air Compressor	109.905	1
IR 185CFM Air Compressor	104.169	1
IR 185CFM Air Compressor	104.182	1
IR 185CFM Air Compressor	104.201	1
Vibro Hammer	700.43	1
Wood Chipper 1	Bayou Tree 5	1
Wood Chipper 2	Bayou Tree 6	1
250T Liebherr	B&G 01	2
315 Excavator	192.019	2
6" Hydraulic Pump	422.042	2
6" Hydraulic Pump	422.043	2
6" Hydraulic Pump	422.048	2
6" Hydraul ic Pump	422.049	2
8" Hydraulic Pump	422.053	2
American Auger - Tri-State	Tri-State1	2
American HC 80 TERE X	225.083	2
American HC 110 TEREX	R226514002	2
Asphalt Milling Machine	482.012	2
Asphalt/MTV	451.016	2
Asphalt Paver	451.030	2
Asphalt Shuttle Buggy	451.028	2
Bobcat	Bayou Tree 7	2
Bobcat BXT	192.047	2
Bobcat Cold Planer	482.011	2
BobCat E35i	10276274	2
Bobcat Skidsteer	371.015	2
CAT 312 Excavator	192.046	2
CAT 312 Excavator	192.049	2
CAT 312 Excavator	192.056	2
CAT 314 Excavator	R192214002	2
CAT 325D Excavator	193.129	2
CAT 325 Excavator	193.130	2
CAT 329 Excavator	LA Rental 00001	2
CAT 329E Excavator	PLW135	2
CAT 345B Excavator	195.035	2
CAT 345c long stick excavator	195.041	2
CAT 312 Puddle jumper	192.048	2
CAT 420F Puddle Jumper	LA Rent 01	2
CAT 420 PJ Puddle Jumper	R191112011	2
CAT D4 Dozer	251.127	2
CAT Excavator	363.040	2
CAT CB-334E Roller	446.024	2
CAT Roller CS-433E	445.015	2
CAT Front-End Loader	520.029	2
Caterpillar Asphalt Paver	451.029	2
Caterpillar Asphalt Paver	451.030	2
Caterpillar Excavator	R193115006	2
Caterpillar Loader/Backhoe	191.445	2
Caterpillar Ldr/Bkh Forks	520.035	2
Deere 310 Puddle Jumper	191.309	2
Deere 310 Puddle Jumper	191.357	2
Deere Dozer	251.113	2
EC35C Mini Excavator	58332-189	2
Excavator	192.069	2
Generator	R471315001	2
Grove RT 500C	221 .052	2
J-Star JD Puddle Jumper	JSTAR0001	2
JD 50D Mini Excavator	192.061	2
JD 270 Excavator	192.039	2
JD 270 Excavator	193.132	2
JD 270c LC Track Hoe	193.120	2
JD 450D Excavator	195.040	2
JD 275 Long Stick	193.131	2
JD 550 Dozer	251.110	2
JD 550 Dozer	251.124	2
JD Dozer	251.102	2
JD Dozer	251.120	2
JD Puddle Jumper	191.426	2
JD Puddle Jumper	191.451	2
JD Puddle Jumper 310SK	191.457	2
Puddle Jumper	191.358	2
Puddle Jumper	191.428	2

Equipment Description	Serial No.	Noise Type
JD Rubber Tire Backhoe	191.428	2
Jet Truck	425.005	2
John Deere 35D Mini-Excavator	JD35D	2
John Deere 50C 2TS Excavator	192.036	2
John Deere 134	192.032	2
John Deere Backhoe 135D	192.057	2
John Deere Dozer	251.119	2
John Deere Excavator	193.115	2
John Deere Excavator - 200C	193.118	2
John Deere 310SK Rubber tire	191.460	2
John Deere Rubber Tire Backhoe 310 SJ	191.409	2
John Deere 310 SK Rubber Tire Backhoe	191.451	2
John Deere Trackhoe 135c RTS	192.041	2
John Deere Trackhoe 135c RTS	192.043	2
Kobelco Crane 85 ton	CK850	2
Komatsu D21P Dozer	250.100	2
Komatsu Bull Dozer	250.101	2
Kubota Generator	471.126	2
Kubota SQ-33 Generator	471.130	2
Link-Belt 50T	224.027	2
Link-Belt 50T	224.026	2
Manitowoc Crane 3900	226.261	2
Manitowoc W 4000	227. 387	2
Offroad Forklift	569076	2
Offroad Forklift	RSC0001	2
Pump Truck (Schwing)		2
Pump Truck (Putzmeister)		2
Pump Truck	511.023	2
Pump	0.00000	2
Roller	446.030	2
Roller	466.031	2
Roller	446.035	2
Rubber Tire Backhoe	191.440	2
Rubber Tire Backhoe	191.434	2
Rubber Tire Backhoe	191.454	2
Rubber Tire Backhoe	R191114002	2
Street Sweeper	431.030	2
Street Sweeper	431 .031	2
Street Sweeper	431.032	2
Street Sweeper	431.033	2
Street Sweeper	829313	2
SunBelt 18" Pump	Sun Belt	2
SunBelt 18" Pump	SunBelt1	2
SunBelt 18" Pump	SunBelt2	2
SunBelt 18" Pump	SunBelt3	2
Takeuchi Mini-Excavator TB016	UR849477	2
Takeuchi Mini Excavator	United Rental	2
Terex HC80	225.087	2
Volvo Backhoe Long Stick	EC300DLR	2
Volvo Long Stick Excavator	EC300DLR-2	2
Volvo Roller	Volvo1	2
Volvo Track hoe	EC300D	2
XP-185 Air Compressor	104.161	2
8-15 Ton Asphalt Roller	446.029	3
10 Ton Fork Lift	rented-000	3
115' Fixed Leads	705.328	3
Bucket Truck	Bayou Tree 1	3
Bucket Truck	Bayou Tree 2	3
CAT Rubber Tire Exc	191.493	3
Caterpillar Fork Carriage	520.470	3
Cherry Picker	HTC0080-01	3
F350	Bayou Tree 8	3
F650	Bayou Tree 3	3
F650	Bayou Tree 4	3
Forklift JLG	569076	3
Fuel Tank 500-550 Gal Skid	711.040	3
JLG Manlift 6005 402116	263.012	3
J.L.G. Sky Trak forklift	521.048	3
Lincoln Welding Machine	163.111	3
Link Belt Cherry Picker - 40/60Ton	224.06	3
Linkbelt Cherry Picker	224.261	3
Linkbelt RTC 8050 50 Ton Cherry Picker	224.026	3
Mi-Jack MJ-40 Travelift	R240014001	3
NES Manlift 860SJ	N55838	3
Peterbilt Tack Truck	502.113	3
RTC 8050 Link Belt Series II Cherry Picker	224.027	3
Service Truck	506.115	3
Swinging Leads 26"X115'	705.001	3
Tool Trailers/Skid	631.180	3
Tool Trailers/Skid	631.184	3
Tool Trailers/Skid	631.208	3
Tool Trailers/Wheeled	631.253	3
Water/Service Truck	502.116	3
Welding Machine	164.421	3

Figure 12
Summary of construction equipment used during the course of the construction project. Source: Author.

19. VIBRATION MONITORING

Vibrations due to all construction activities including driving sheet piles will be monitored. The Contractor shall perform the work in a manner which will limit vibrations at the structure nearest to the work being performed to a maximum of 0.25 inch per second. Vibrations will be monitored by others at all structures, including buildings and pools. The Contractor will be informed when the vibrations from his operation have exceeded the 0.25 inch per second limit and the Contractor shall take immediate action to reduce the vibrations to acceptable limits. The Contractor shall give the [redacted] notice at least 15 days prior to beginning vibration-inducing construction operations, and shall coordinate the daily location of these operations with the government personnel at least 48-hours prior. The Contractor shall also be responsible for contacting the vibration monitoring firm to schedule the necessary vibration monitoring personnel.

Figure 13
Excerpt from the project specifications addressing vibration monitoring. Source: Discovery Docs.

Project Documentation — Vibrations

Documentation for the project generated during discovery was reviewed and included: the project plans and specifications; contractor submittals and RFIs; contractor daily field reports; and contractor photos. A review of the project specifications identified requirements for construction-induced vibrations as well as the vibration monitoring requirements. The project specifications (**Figure 13**) required the utility to contract with an independent company to monitor vibrations "at all structures, including buildings and pools."

A consulting engineering firm (vibration consultant) was retained by the utility. The vibration consultant used two alpha-seismite digital seismographs. These instruments were manually monitored in lieu of more rapid and reliable automated reporting arrays.

The author notes that for a project as extensive as this, automated arrays provide far superior data collection and alert systems as they can be installed at the beginning of the project and used as a basis for interpolating across the project site. Empirically based 2D propagation maps can be generated to better manage construction-induced ground vibrations and overcome manually placed monitors too far from the construction work in order to characterize vibrations at the "structure nearest the work being performed," as required by the project specifications.

Reports were prepared daily by the on-site vibration consultant personnel that listed the maximum PPV values recorded, a general description of the monitoring location (including a sketch by the vibration monitoring technician), and notations of general construction activities in the vicinity of the vibration monitoring.

Noise Baseline Conditions

While the noise literature provides some guidance on noise levels, data was collected during the time forensic engineering analyses and reporting were underway by a specialty sound consultant. This work occurred after completion of the project, so results were inferred to be representative of pre-project conditions. Sound measurement devices were placed at select locations along the historic construction right of way (**Figure 14**). (Note: The construction right of way per the project drawings essentially terminated at the residential property lines along the sidewalk).

Continuous sound recordings were made over the course of one week across the former project site. An overlay, based on time period, is presented in **Figure 15**. Each color plot represents a different location along the construction route. Spikes in the time histories are typically the result of emergency response vehicles (police, fire, ambulance). The low bound ambient noise level during the course of the "work day" (8 a.m. to 5 p.m.) is approximately 55 dB and a high of approximately 67 dB. This range is consistent with the published literature of anticipated noise levels for an "urban residential area."

The measured ambient background noise closely matched the ranges reported in the published literature

Figure 14
Example configuration of a sound monitoring location set up at the historic construction right of way. Source: Sound consultant.

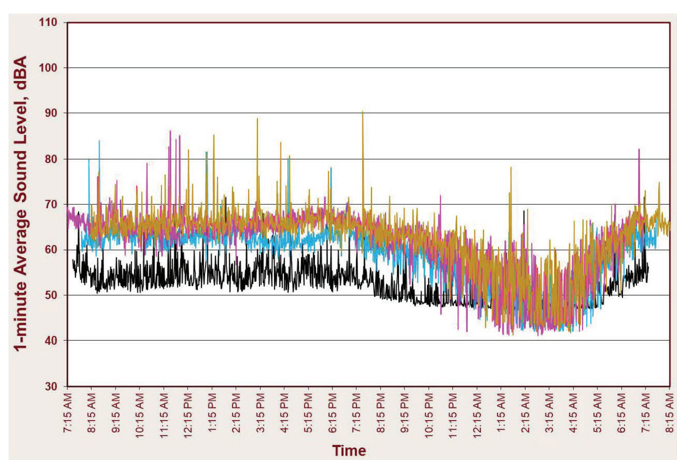


Figure 15
Representative ambient background sound levels along the construction route limits. Source: Sound consultant.

(**Figure 16**). The construction noise levels in excess of 85 dB result in a noise difference of 20 to 30 dB from baseline level at 60 dB, which, according to the published literature of community reaction (**Figure 3**), predicts strong reaction from the community. Community complaints were one of the plaintiff's claims against the utility. A-weighting was used, which is a standardized filter used to alter the sensitivity of a sound level meter with respect to frequency so that the instrument is less sensitive at low and high frequencies where the human ear is less sensitive — also written as dBA.

Construction Noise Analysis

The forensic noise analysis consisted of reviewing the inventory of equipment listed on each of the contractor's daily field report (**Figure 11**). Each piece of equipment was classified into one of three noise categories, based on the published literature identifying typical noise levels based on general equipment type:

- Red – more than likely in excess of 85 dB.
- Yellow – likely in the range of 85 dB.
- Green – likely less than 85 dB.

The maximum noise producing equipment on the project for each day was summarized and plotted on a calendar (**Figure 17**) to show the court the chronic and routine exceedance of the noise threshold (85 dB) at the construction easement.

A major challenge was documenting the specific

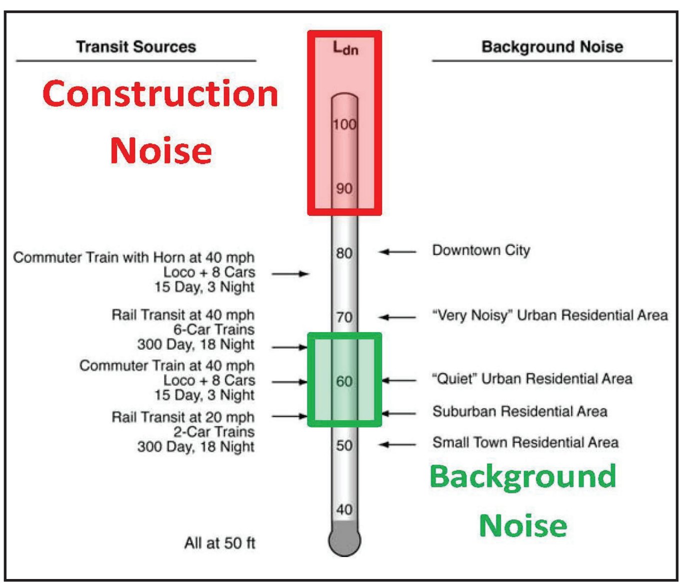


Figure 16
Comparison of construction noise levels relative to ambient background levels[17].

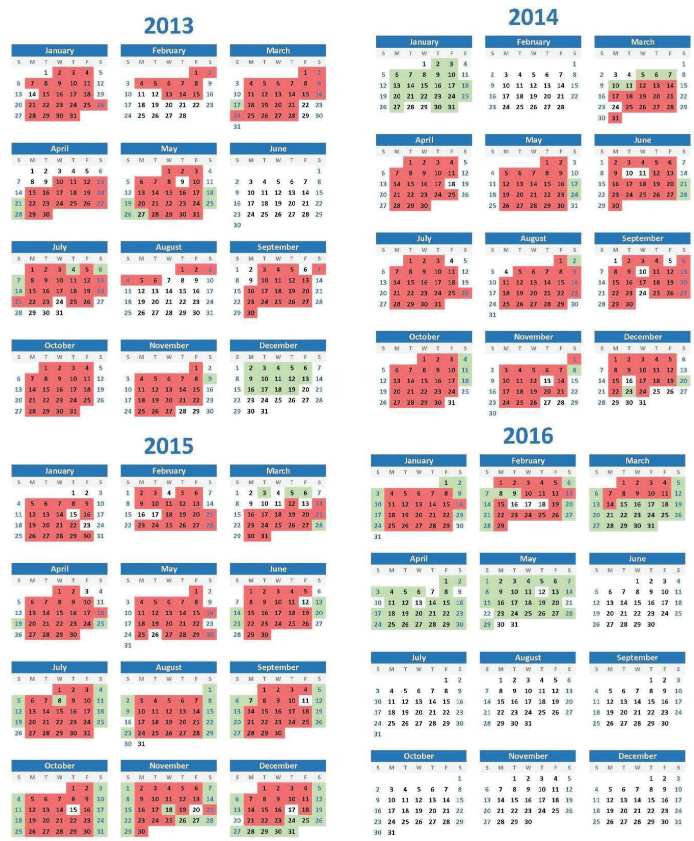


Figure 17
Summary of daily maximum noise level based on utilized contractor equipment over the course of the project. Source: Author.

locations of the equipment for each day to more precisely map the "noise zone" associated with the utilized equipment, but the documentation made available was insufficient to accomplish this in a reasonable manner. The contractor did provide a phased construction schedule for the project as a whole. This over-arching schedule was used to infer the general regions impacted by the equipment noise.

The work varied spatially across the work area throughout the day and throughout the project duration. The width of the work limits was generally on the order of 85 ft. The typical distance of the residential structures and

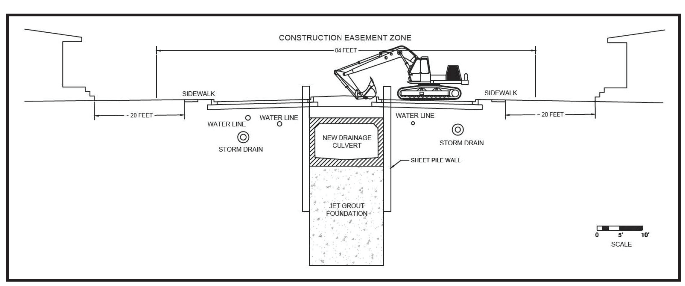


Figure 18
Typical configuration showing construction easement zone and proximity of adjacent residential structures. Source: Author.

the construction easement (**Figure 18**) was on the order of 25 ft.

Counter claims were made that the majority of the residents were away during the work day, and, as a result, were not inconvenienced by these exceedances. While an intriguing argument, it has no merit due to the fact that: (1) the project specifications clearly limit the maximum noise level to 85 dB at the construction easement irrespective of the time of day; (2) no effort was made by either the utility or the contractor to survey the adjacent residents if they were bothered by the noise; and (3) repeated complaints were made by the residents to a project complaint line regarding the construction noise and disruption of their use and enjoyment during the construction project.

It was also argued that the noise level inside the residential structures was likely less than 85 dB due to attenuation through the structure's framing. However, this argument also had no merit due to the fact that the project specifications restricted the noise to a maximum of 85 dB at the construction easement, not at the residential structure or inside the residential structure.

Courtroom Demonstrative — Noise

A courtroom demonstrative was developed to convey to the court the concepts of amplitude, frequency, and time pattern associated with noise, where[17]:

Amplitude — Loudness of a sound as a result of differences between the extremes of an oscillating sound.

Decibel — The standard unit of measurement for sound pressure level and vibration level. Technically, a decibel is the unit of level that denotes the ratio between two quantities that are proportional to power; the number of decibels is 10 times the logarithm of this ratio, also written as dB.

Frequency — The number of times that a periodically occurring quantity repeats itself in a specified period. With reference to noise and vibration signals, the number of cycles per second.

Time Pattern — Variation of noise over time.

The most important element of the demonstrative was communicating the relationship between amplitude and reported dB level. Because an increase of 1 dB is a tenfold increase in sound pressure levels, illustrating the sound levels was important to ensure there was an appreciation between a sound at 85 dB and 95 dB.

The demonstrative was configured so that speakers were oriented toward the judge, and sound levels were calibrated to reach the intended sound level (dB) at an offset distance of 20 ft (distance between the speakers and the judge). Sound meters were positioned at the judge's location to verify the intended dB level was achieved.

A portfolio of sounds was recorded from construction activities. Some recordings were based on current work in remaining areas of work for the drainage improvement project. Other recordings were based on video captured by residents during the course of the work. The recordings included (**Figure 19**):

- Ambient traffic noise (55 dBA & 65 dBA)
- Concrete breaker (85 dBA)
- Concrete saw (90 dBA)
- Roller compactor (95 dBA)
- Pile driver (100 dBA to 115 dBA)

While earplugs were made available to safely experience the full portfolio of recorded sounds, the court requested the demonstrative terminate upon reaching the 90 dBA example as the noise levels became very disagreeable.

Construction Vibration Analysis

Over the course of the construction project, 763 vibration reports were reviewed and tabulated. Of those reports, approximately 44% had daily maximum PPV values equal to or greater than 0.25 in./second (**Figure 20** and **Figure 21**) throughout the project area.

Figure 21 presents a spatial plot of setup locations of the vibration monitoring equipment and scaled circles are associated with each monitor location with a max PPV greater or equal to 0.25 in. per second. The recordings are representative of the ground vibrations observed at the unique vibration monitor location from all surrounding vibration sources.

Vibrations attenuate over distance. While the project specifications require monitoring "at the closest structure," the vibration monitors were frequently situated at more distant structures, with no monitoring at the "closest

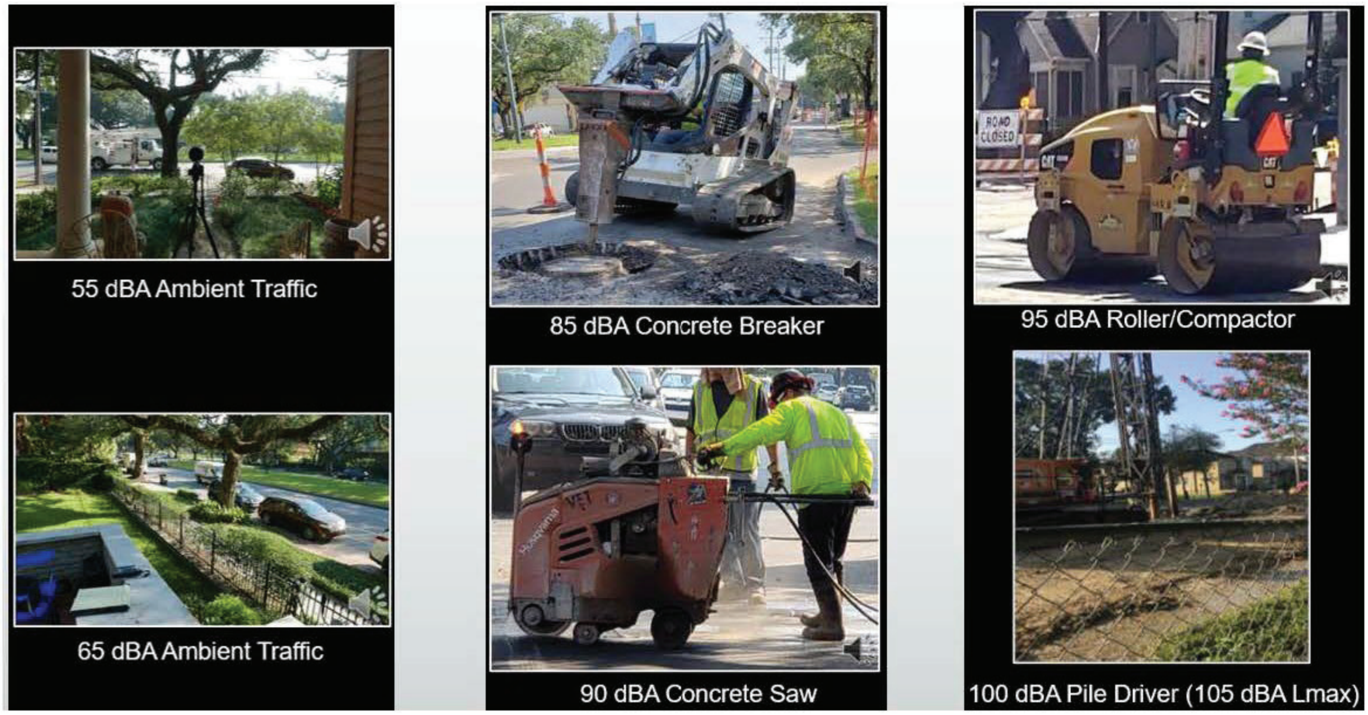


Figure 19
Overview of sounds included in the courtroom demonstrative. Source: Sound consultant.

structure" as required by the project specification.

The reported ground vibrations do not represent the maximum construction-induced vibration "the nearest structure" would experience. **Figure 22** shows a photo taken by the contractor during the course of the work where the vibration monitor was not situated in a position to represent construction-induced ground vibrations 'at the nearest structure. Additionally, numerous field reports note work occurring at significant distances from the vibration monitor, as shown in **Figure 23**.

These factors lead to "under-reporting," where the reported values do not satisfy the project specifications, which require reporting values at the "nearest structure," rather than "at the monitoring device."

The PPVref value was back-calculated to establish the ground vibration magnitude at a distance of 25 ft. Thus, if the vibration monitor was located more than 25 ft from the

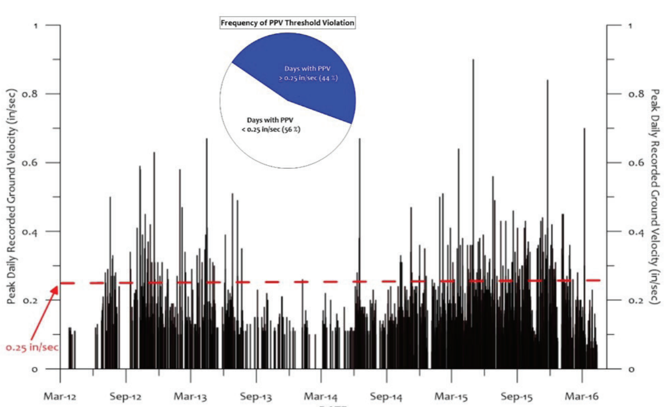


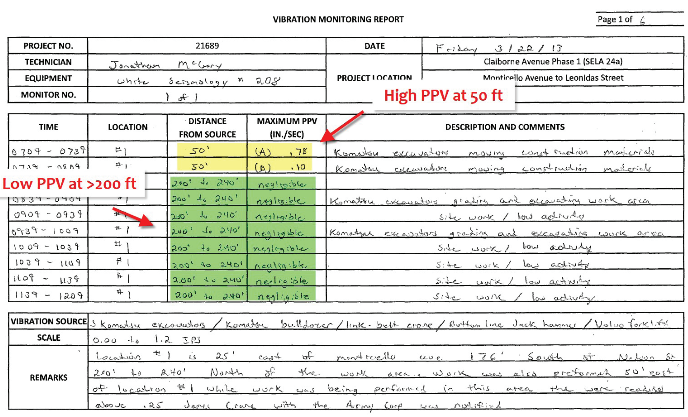
Figure 20
Vibration monitoring days where the maximum PPV exceeded the allowable threshold. Source: Author.

Figure 21
Plot of recorded maximum daily PPV values (in./second). Source: Author.

source, the equivalent PPV at 25 had to be back-calculated. Following establishment of the PPVref, vibration magnitudes based on distance were calculated and reported as PPVequiv. Results are illustrated in **Figure 27** through **Figure 30**.

The dashed blue line in **Figure 27** through **Figure 30** delineate the construction easement. As can be seen in the attenuation results, construction-induced ground vibrations exceeding the project threshold of 0.25 in. per second extend well beyond the project construction easement. As a result, the construction-induced ground vibrations were determined to be "substantial factors of harm" to the adjacent structures.

Figure 22
Example where vibration monitor was not situated at a location representative of vibrations experienced "at the nearest structure." Source: Discovery Docs.



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PROJECT NO.	21689	DATE	Friday 3/22/13
TECHNICIAN	Jonathan McGary	PROJECT LOCATION	Claiborne Avenue Phase 1 (SELA 24a)
EQUIPMENT	White Seismology # 208		Monticello Avenue to Leonidas Street
MONITOR NO.	1 of 1		

TIME	LOCATION	DISTANCE FROM SOURCE	MAXIMUM PPV (IN./SEC)	DESCRIPTION AND COMMENTS
0709 - 0739	#1	50'	(A) .78	Komatsu excavator moving construction materials
0739 - 0809	#1	50'	(B) .10	Komatsu excavator moving construction materials
		200' to 240'	negligible	
0839 - 0909	#1	200' to 240'	negligible	Komatsu excavators grading and excavating work area
0909 - 0939	#1	200' to 240'	negligible	site work / low activity
0939 - 1009	#1	200' to 240'	negligible	Komatsu excavators grading and excavating work area
1009 - 1039	#1	200' to 240'	negligible	site work / low activity
1039 - 1109	#1	200' to 240'	negligible	site work / low activity
1109 - 1139	#1	200' to 240'	negligible	site work / low activity
1139 - 1209	#1	200' to 240'	negligible	site work / low activity

VIBRATION SOURCE	3 Komatsu excavators / Komatsu bulldozer / link-belt crane / Bottom line Jack hammer / Volvo forklift
SCALE	0.00 to 1.2 IPS
REMARKS	Location #1 is 25' east of monticello ave 176' South of Nelson St 200' to 240' North of the work area. Work was also preformed 50' east of location #1 while work was being performed in this area the were readings above .25 James Crane with the Army Corp was notified

Figure 23
Example daily vibration monitoring report.
Source: Discovery Docs; notes by author.

Location (I)		
PPVref	D	PPVequip
0.66	25	0.66
0.66	5	7.38
0.66	30	0.50
0.66	35	0.40
0.66	40	0.33
0.66	45	0.27
0.66	50	0.23
0.66	60	0.18
0.66	70	0.14
0.66	80	0.12
0.66	90	0.10
0.66	100	0.08
Dist to 0.25 ips	*48*	0.25

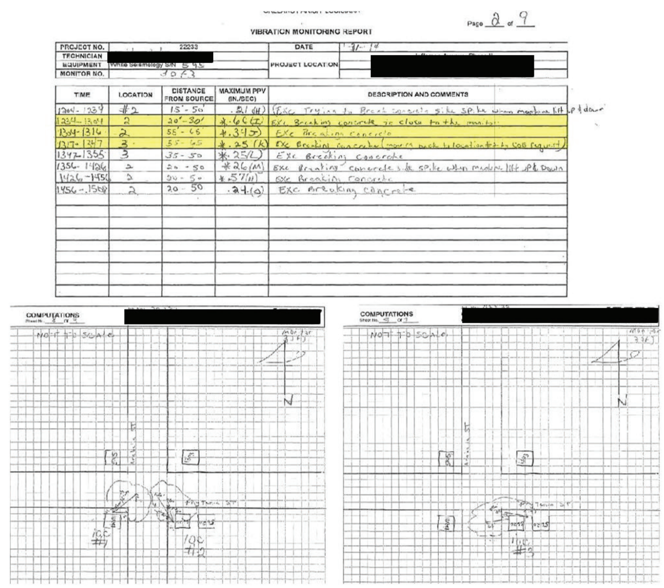
Location (J)		
PPVref	D	PPVequip
1.26	60	0.34
1.26	5	14.13
1.26	30	0.96
1.26	35	0.76
1.26	40	0.62
1.26	45	0.52
1.26	50	0.45
1.26	60	0.34
1.26	70	0.27
1.26	80	0.22
1.26	90	0.19
1.26	100	0.16
Dist to 0.25 ips	*74*	0.25

Location (K)		
PPVref	D	PPVequip
0.93	60	0.25
0.93	5	10.39
0.93	30	0.71
0.93	35	0.56
0.93	40	0.46
0.93	45	0.38
0.93	50	0.33
0.93	60	0.25
0.93	70	0.20
0.93	80	0.16
0.93	90	0.14
0.93	100	0.12
Dist to 0.25 ips	*60*	*0.25*

Figure 24
Construction-induced ground vibration attenuation calculation. Source: Author.

Conclusion

A lawsuit was filed by residents situated adjacent to a major urban drainage improvement construction project in a historic district against the utility owner (utility) for damages, including physical distress and loss of use as a result of the construction activities. This study performed



VIBRATION MONITORING REPORT — Page 2 of 9

PROJECT NO.	22233	DATE	1-31-14
TECHNICIAN	[redacted]	PROJECT LOCATION	[redacted]
EQUIPMENT	White Seismology S/N 595		
MONITOR NO.	3 of 3		

TIME	LOCATION	DISTANCE FROM SOURCE	MAXIMUM PPV (IN./SEC)	DESCRIPTION AND COMMENTS
1204-1234	#2	15'-50'	.21 (H)	(Exc Trying to Break concrete spike spike when machine lift up & down
1234-1304	2	20'-30'	*.66 (I)	Exc Breaking concrete in close to the monitor
1304-1316	2	55'-65'	*.34 (J)	Exc Breaking concrete
1317-1347	3	55-65	*.25 (K)	Exc Breaking concrete (move back to location #2 by SOB request)
1347-1355	3	35-50	*.25 (L)	Exc Breaking concrete
1356-1426	2	20-50	*.26 (M)	Exc Breaking concrete side spike when machine lift up & Down
1426-1456	2	20-50	*.57 (N)	Exc Breaking concrete
1456-1508	2	20-50	.24 (O)	Exc Breaking concrete

COMPUTATIONS [redacted] NOT TO SCALE N

COMPUTATIONS [redacted] NOT TO SCALE N

Figure 25
Calculation of vibration attenuation from January 31, 2014. Source: Discovery Docs.

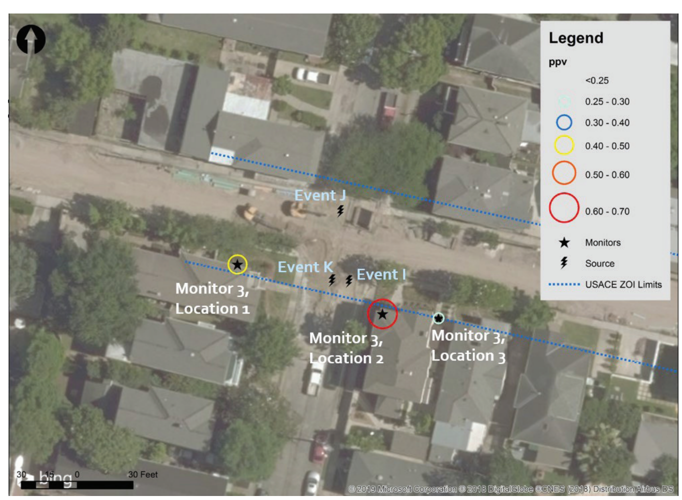


Figure 26
Location of construction-induced ground vibration attenuation example with three monitor setup locations and three exceedance events. Source: Author.

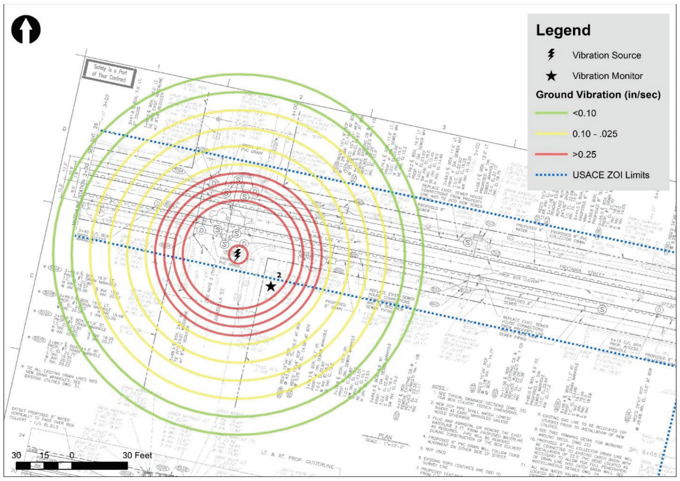


Figure 27
Attenuation of Event "I" with project plan overlay showing event origin relative to planned work. Source: Author.

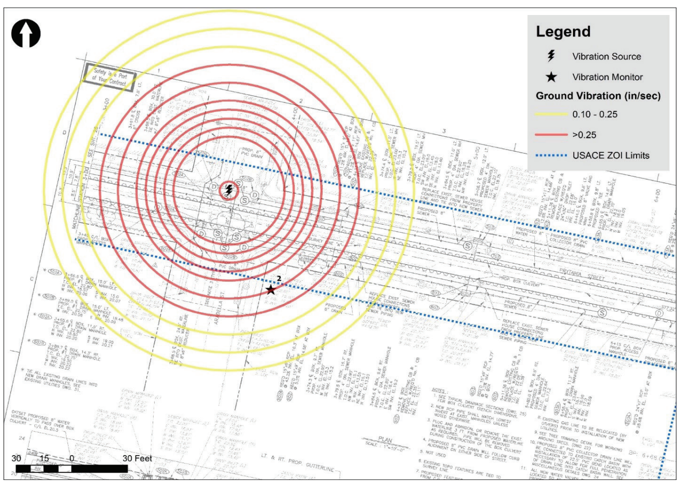


Figure 28
Attenuation of Event "J" with project plan overlay showing event origin relative to planned work. Source: Author.

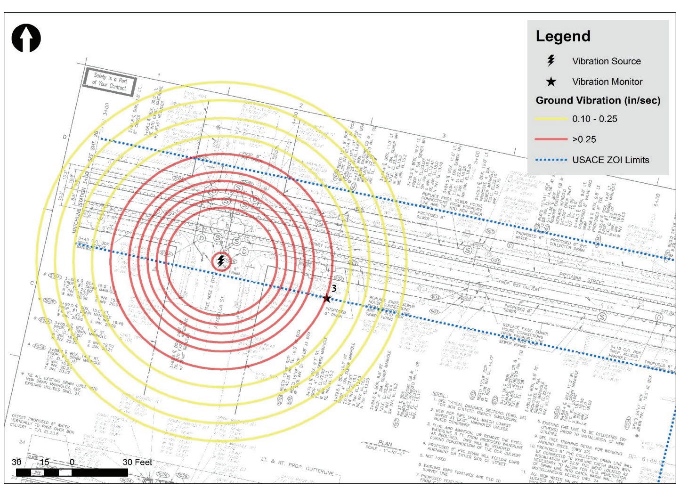


Figure 29
Attenuation of Event "K" with project plan overlay showing event origin relative to planned work. Source: Author.

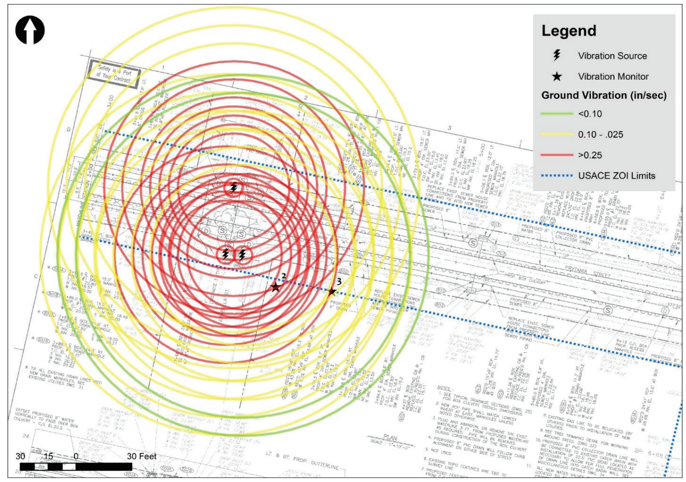


Figure 30
Overlay of attenuation of all three events (I, J, and K). Source: Author.

an FE of construction-induced noise and ground vibrations impacting residents near the construction activities.

Noise data collected during the course of the drainage project were used to create a "time history" of daily maximum noise levels. These maximum noise levels were contrasted with the maximum allowable per the project specifications. The FE found significant deviations from the required data collection protocols and routine violation of the maximum allowable thresholds specified for the project.

Attenuation relationships were used to delineate ground vibration extents and magnitudes propagating from the source to adjacent receptors (i.e., structures). The FE found significant deviations from the required data collection protocols and a high degree of "under-reporting." Construction-induced ground vibrations were determined to be "substantial factors of harm" to the adjacent structures.

The case was tried in state court via bench trial. The court's decision mirrored the findings of the forensic analyses.

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