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Scientific Investigations Report 2018–5129

U.S. Department of the Interior
U.S. Geological Survey

Front cover photo. Indiana bat, *Myotis sodalis*, by Ann Froschauer, U.S. Fish & Wildlife Service.

Back cover photo. Indiana bats, *Myotis sodalis*, by Andrew King, U.S. Fish & Wildlife Service.

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U.S. Geological Survey
James F. Reilly II, Director

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)

Datum

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviations

Hz	frequency units in hertz
in/s	inch per second
in/s^2	inch per square second
S/N	serial number
USGS	U.S. Geological Survey

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Abstract

Vibrations originating from construction of a new walkway in a passage of Mammoth Cave, from walking personnel simulating a bat survey, and from ambient sources were measured near a bat hibernaculum at Mammoth Cave National Park, Kentucky, to determine if the vibrations were disturbing the hibernating bats. Data presented indicate direction and magnitude of the vibrations. The seven sources of vibration that were recorded include hammer drill (one location), plate compactor (two locations), jackhammer (two locations), personnel simulating a bat survey near the hibernaculum (walking throughout the cave), and background levels. Vibrations were measured for approximately 10 seconds during each triggering of the source and each source was recorded 5–10 times to represent the reproducibility of the vibrations.

The plate compactor produced the largest velocity of 0.00226 inch per second on one of the longitudinal components. The simulated bat survey produced the largest value of acceleration of 0.34 inch per square second in the vertical component. Maximum vertical velocities and accelerations did not exceed literature values for human perception or visible agitation in laboratory mice.

Introduction

Mammoth Cave National Park (fig. 1) is a hibernaculum where dormant endangered Indiana bats (*Myotis sodalis*) shelter during winter months. A passage in Mammoth Cave known as Cyclops Gateway (not shown) is near a hibernaculum and roost of the endangered Indiana bat. During construction of a new walkway in Mammoth Cave in winter 2016, vibrations from nearby construction activities were felt in the Cyclops Gateway. Potential sources of the vibrations felt in the passage included the construction activities, personnel walking in the cave, and ambient vibrations from natural sources. The National Park Service requested the assistance of the U.S. Geological Survey (USGS) to monitor the vibration levels near the bat hibernaculum to determine if construction-induced vibration may be of sufficient magnitude to induce observed activity of the bats.

Mammoth Cave is a United Nations Educational, Scientific and Cultural Organization World Heritage site; it is the longest cave system in the world, presents many types of cave formation, and has one of the world's most diverse fauna (United Nations Educational, Scientific and Cultural Organization, 2017). The cave system is in a low plateau of karst limestone of Mississippian age (fig. 2). The soluble limestone units that form the cave system are protected by a series of sandstones. The sandstones form a cap that reduces the erosion of the upper passageways of the cave (Palmer, 1981). Water drains from the cave to the Green River (fig. 1) northwest of the study site.

Disturbance of hibernating bats from human activity is recognized as an important element in the decline of Indiana bats within its range (Delaney, 2002). Arousing bats during hibernation can reduce fat reserves in bats and can affect species survival. For example, other researchers identified that a colony of big brown bats (*Eptesicus fuscus*) that were exposed to nighttime construction activity developed a combination of lethargy, weight loss, and hemorrhage and were diagnosed with hepatic lipidosis because of exposure to an environmental stressor (Snyder and others, 2015).

Monitoring of human-induced and natural vibrations can be an important part of mitigating construction-related and other operational disturbance of habitat in natural settings like Mammoth Cave. Monitoring systems have been used by USGS scientists to investigate the effects of natural vibrations on the structural integrity of man-made construction (Kalkan and others, 2012; King and others, 1988). Seismic instruments can also be deployed to record how the instruments respond to vibrations in and around buildings and structures (Çelebi, 2000). The USGS provides scientific information such as the seismic data in this study to describe the interaction of geologic systems with human and natural phenomena to better understand effects on ecosystems like the bat hibernaculum and on property. The USGS works within its strategic science direction and with its cooperative partners, including Department of Interior partners such as the National Park Service, to document these emerging hazards and to assure that scientific methods are applied effectively to understand these phenomena and, thereby, minimize loss of habitat and ecosystem services.

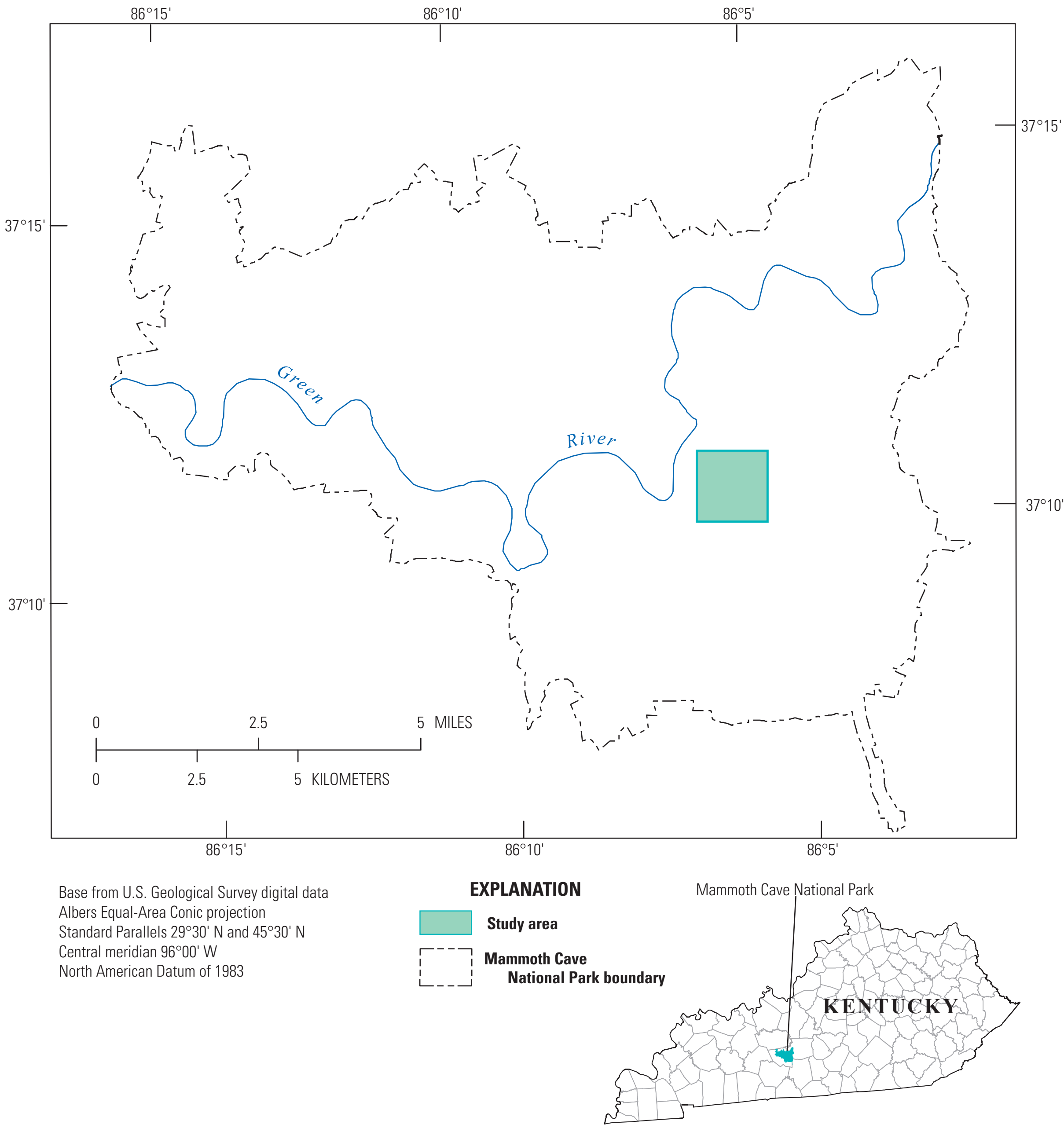


Figure 1. The location of Mammoth Cave National Park with inset map of the State of Kentucky.

An investigation by the USGS, in cooperation with the National Park Service, was done to detect vibrations near a bat hibernaculum at Mammoth Cave National Park, Kentucky, and to understand the possible relation of vibrations to the operation of specific construction equipment and to ambient manual construction and footfall sources. The work was done in a cave passage at Mammoth Cave accessed through a feature known as Cyclops Gateway. Cyclops Gateway is a side passage off the main cave that is along the Historic Trail. The exact location of the cave passage and hibernaculum in Mammoth Cave are not shown to protect the bat colony.

Period	Series	Formation	Principal lithology	Maximum formation thickness, in feet, and approximate stratigraphic location of Mammoth Cave	
Pennsylvanian	None	Caseyville	Sandstone with conglomerate at base; conglomerate is unconformable with Glen Dean, Hardinsburg, Haney, Big Clifty, and Girkin Formations	0–350	
Mississippian	Chester	Leitchfield	Shale	0–160	
		Glen Dean	Limestone	0–50	
		Hardinsburg	Sandstone	0–60	
		Haney	Limestone	0–40	
		Big Clifty	Sandstone with shale	50–60	
		Girkin	Limestone with shale	135–140	**Mammoth Cave**
	Meramec	Ste. Genevieve	Limestone with chert nodules, dolomite, and shale	110–120	**Mammoth Cave**
		St. Louis	Limestone with chert nodules, dolomite, gypsum, and shale	175–200	**Mammoth Cave**
		Salem	Limestone with chert nodules, dolomite, and shale	70–90	
		Harrodsburg	Limestone with chert nodules and shale	30–80	
	Osage	Fort Payne/Borden	Limestone with chert nodules and shale	300	
	Kinderhook	Chattanooga	Shale	0–100	
Devonian					

[1]Adapted from Palmer (1981).

Figure 2. Stratigraphic diagram showing the rock formations in which the Mammoth Cave system is located.

Purpose and Scope

The purpose of this report is to present data and results from a vibration monitoring survey near a bat hibernaculum in Mammoth Cave. Vibration data were collected during March 2016 to characterize the vibration signature of individual pieces of construction equipment (jackhammer, plate compactor, and hammer drill), from human activity during a simulated bat survey, and from ambient levels during a period of no construction activity in the cave. Vibration data were compiled in a series of plots and tables in terms of the velocity and acceleration of vibrations measured by the monitoring devices. Vibration values recorded in the cave were compared with values derived from other reports studying the effects of vibration of other animals as well as human perception levels. Vibration values reported by this study represent the maximum velocity and acceleration values recorded during each triggering of a source.

Vibration Monitoring Methods

Vibration data were collected for the study during seven vibration source trials at one of two locations in the cave passage on March 15–16, 2016 (fig. 3). Each vibration trial consisted of an array of sensors at different points of the passage monitoring a single vibration source created at a single location. The sources used at location 1 involved impacting loose rock leftover from construction. Sources used at location 2 impacted the cave floor. Each vibration source was monitored during 5–10 repetitions of the source lasting 10 seconds each and separated by at least 1 minute of no activity. All construction activity in the test vicinity was halted before and during each vibration trial. The sound sources were as follows:

- Hammer drill at location 1,
- Plate compactor at location 1,
- Plate compactor at location 2,
- Jackhammer at location 1,
- Jackhammer at location 2,
- Simulated bat survey, and
- Ambient vibration—this trial monitored conditions when the cave did not have construction activity and did not have foot traffic.

For the ambient vibration trial, vibrations were monitored during a period of typical construction activity in the cave with the exception that no work was done with any of the sound sources. Sounds recorded during this period include the passage of workers to the work site farther down from the passageway toward Giant's Coffin (not shown), running of power tools like saws and drills at the work site, and a radio playing music.

For the simulated bat survey, a single person walked the route to the hibernaculum that would be accessed by a biologist to evaluate hibernaculum population and condition. The sound source (a single person) started at the entrance to Cyclops Gateway and walked back toward the location of the bats, moving in 10 second increments. When at least 10 seconds had passed, the source would stand in place until the trial was recorded; the source would proceed when the instruments were ready to record another trial. During each vibration trial, 10 repetitions (recordings) were taken of each source, except for the simulated bat survey, which was limited to 5 repetitions (recordings). The ground velocity and acceleration data discussed in this report are provided in the accompanying data release (Adams and others, 2018).

Vibration and Acceleration Sensor Deployment

During the seven vibration trials, eight geophones and two, one-component accelerometers were placed in the Cyclops Gateway passage to monitor the distribution of vibrations (fig. 3). Each sensor was placed on an unbroken section of the cave wall or floor to ensure the best connection to the limestone that forms the cave. All sensors were leveled using their integral bubble levels or a hand-held spirit level and then oriented horizontally such that the positive deflection of the longitudinal component (defined by an arrow on the sensors) was pointing toward the west wall of the cave perpendicular to the axis of the cave passage. This arrangement has the transverse component deflecting positively to the north, along the axis of the cave. The vertical component was oriented at 90 degrees to both the longitudinal and transverse component and deflected positively toward the ceiling. Sensors were weighted with sandbags or mounted to steel plates to assure good contact with the cave wall or floor. Once the sensors were emplaced, they remained fixed throughout the trials to assure comparability of vibration data among the trials and to minimize disturbance to the bats.

Sensors and other equipment locations were determined using a Leica DistoX™ combination distance meter, compass, and clinometer. Sensor and equipment locations were referenced horizontally and vertically using previous established survey marks associated with the Mammoth Cave National Park cave map (National Park Service, written commun., 2016).

Geophones were used for this survey to record the magnitude of ground motion using calibrated weights and springs. These geophones are mechanical sensors in which a metal weight moving within a coil of wire produces a voltage relative to the motion of the geophone. This voltage is transmitted through wires to a seismograph where the voltage was recorded.

Throughout the survey, three-component surface geophones were used to record vibration velocity and connected to a Geometrics Geode™ seismograph (serial number [S/N] 4394). The three-component surface geophones record transverse, longitudinal, and vertical orientations of vibration velocity. The geophones are manufactured by R.T. Clark™ (no S/N; referenced by colored tape) and have a frequency of 10 hertz (Hz), coil resistance of 395 ohms, and a sensitivity of 0.7 volt per inch per second (fig. 4). The seismograph sampled these geophones at a rate of 4,000 samples per second for 8 seconds.

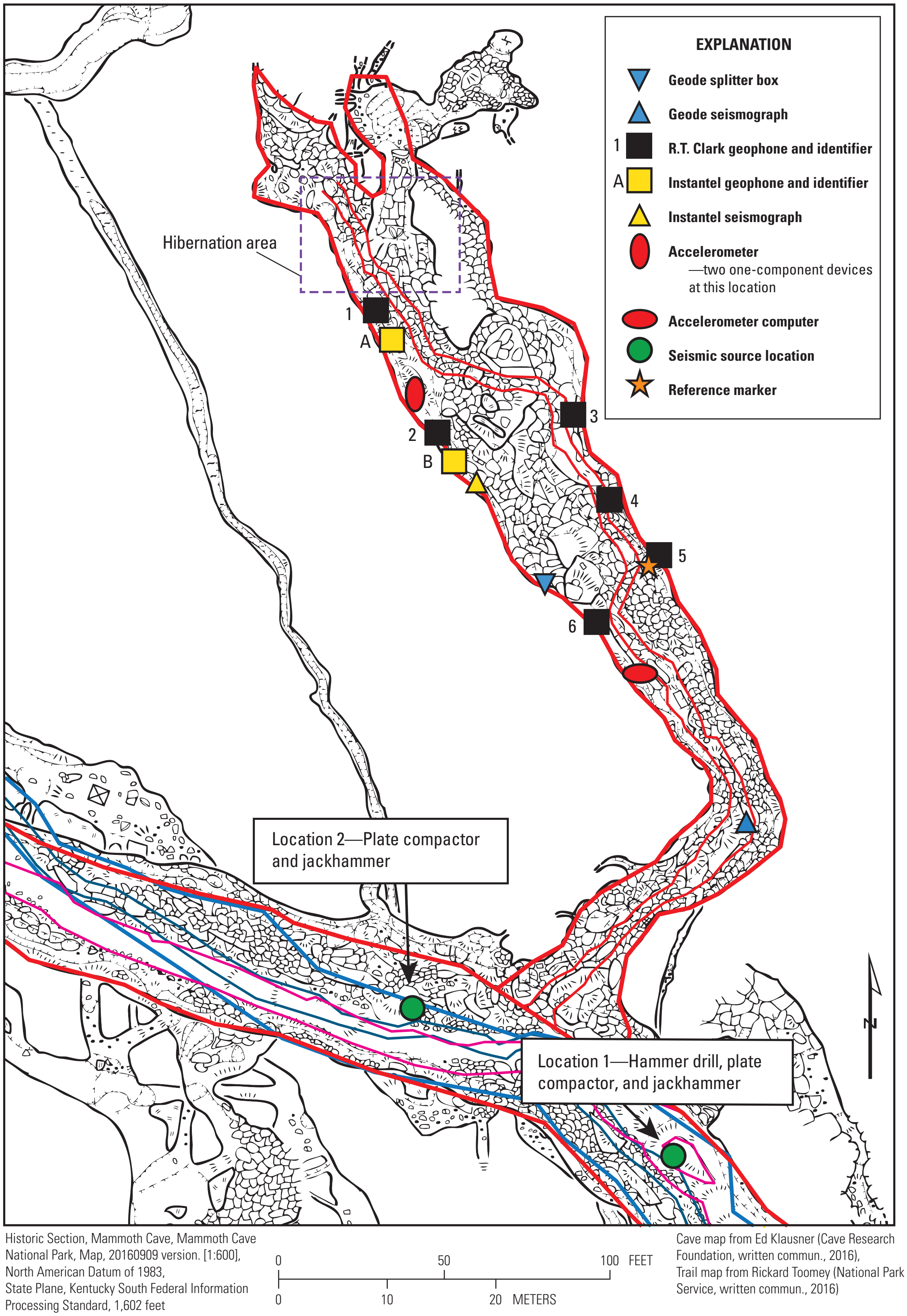


Figure 3. Portion of the Mammoth Cave National Park cave map with locations of vibration sources and sensors deployed for this study. Red lines on the map indicate navigable areas of the cave. Blue and pink lines indicate different limits of construction activity within the cave.

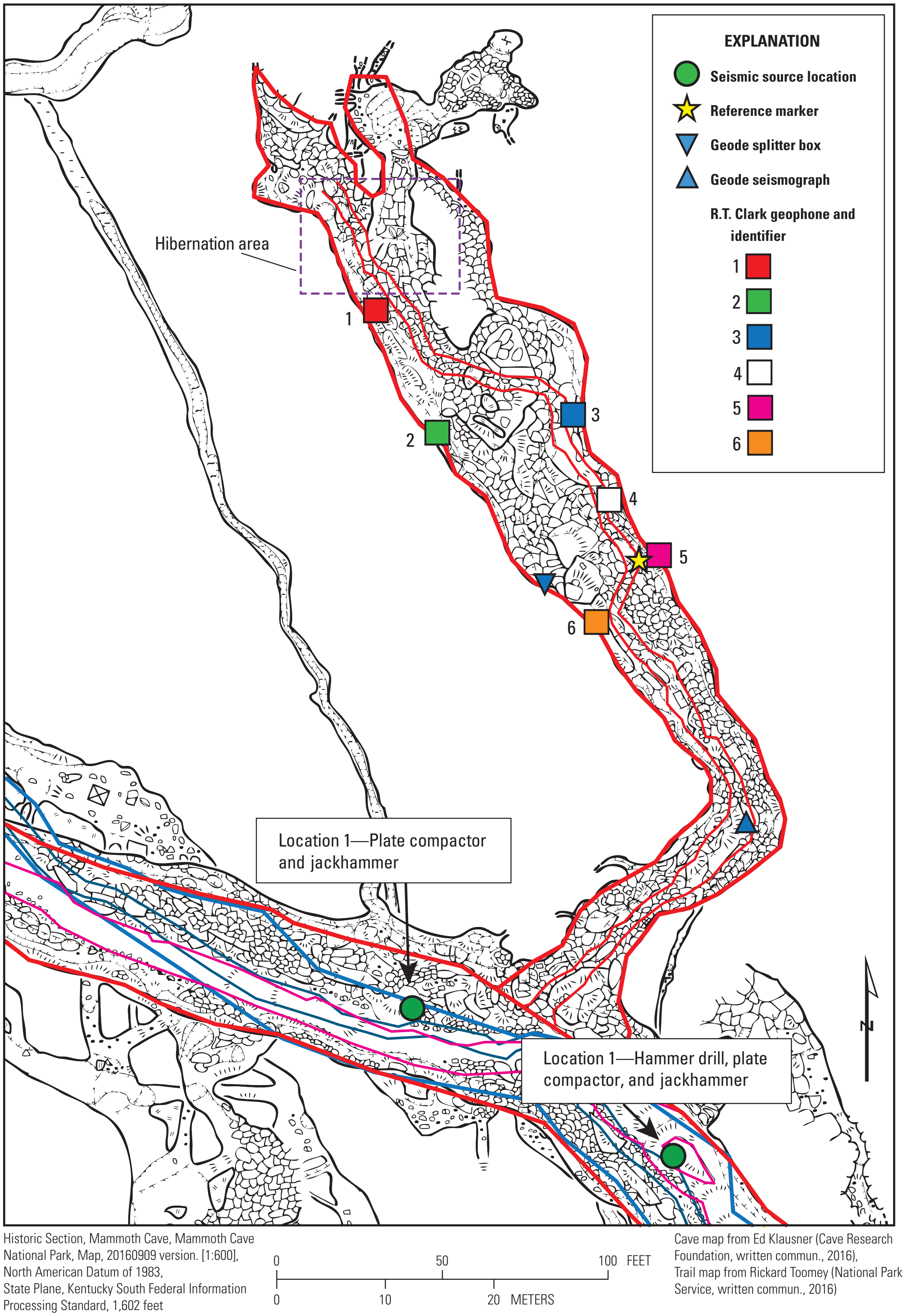


Figure 4. Portion of Mammoth Cave National Park cave system with locations of vibration sources and R.T. Clark geophones deployed for this study. Color code and numbers for geophone symbols used in figure 7. Red lines on the map indicate navigable areas of the cave. Blue and pink lines indicate different limits of construction activity within the cave.

Two additional three-component geophones (Instantel™ 720A2001 type, S/Ns SE12937 and SE13003) used for this survey were calibrated by the International Society of Explosive Engineers before field work began. These geophones have a frequency of 2 Hz and a resolution of 0.00031 inch per second (in/s). The geophones were sampled at a rate of 4,000 samples per second by a Minimate Pro6™ seismograph (Instantel, S/N MP13203).

Acceleration was recorded for this survey using two, one-component accelerometers (PCB Piezotronics™, 393B12 type, S/Ns 35277 and 35276) at one location. Each one-component accelerometer was positioned to record either vertical or horizontal orientations of vibration-related acceleration. These sensors were sampled at 8,000 samples per second by a data acquisition system (National Instruments cDAQ–1971™, S/N 17126F8), shown in figure 3 as the accelerometer computer. These sensors have a sensitivity of 3.708 volts per inch per second.

Data Processing

Vibration sources were recorded during each trial during 10 repeated events, except during the simulated bat survey, which was limited to 5 repeated events. For each repetition of each source (recording), the maximum vibration or acceleration value recorded during the 8–10 seconds of data collection was recorded. For each source, the largest of the 10 maximum values recorded for all vibration source trials, except the simulated bat survey, and the largest of the 5 maximum values recorded for the simulated bat survey are used to interpret acceleration and velocity responses at the geophone sites. Accelerometer data were recorded as voltage values from the sensors and converted directly to inch per square second using the sensor sensitivity.

Geophone data were converted from a binary SEG–2 format to text format by using an American Standard Code for Information Interchange (ASCII) conversion available in Geopsy™ software (Geopsy Project, 2016). Because both geophone models have flat responses above their respective corner frequencies (10 Hz for the R.T. Clark geophones; 2 Hz for the Instantel geophones), the conversion from millivolt to inch per second is a linear application of the geophone sensitivity.

Limitations of Vibration Monitoring Method

This study was done in a very complex, three-dimensional environment. The bats were high up on the walls of the chamber, and the construction vibrations were applied to the floor of the larger passageway outside. The experiment was done on the assumption that the walls and floor of the two cave sections are homogenous and isotropic; however, to verify that the seismic signals were not attenuated by either their ray path through the rock or features within the rock was not possible.

Sensor coupling to rock surfaces was a challenge because the cave was an active archeological site and because of the presence of the bats. The need to prevent disturbance to cave surfaces and damage to the archaeological site and bat habitat precluded use of several practices to improve sensor coupling to rock. Every effort was made to place the various sensors on solid rock within the cave, however, they could not be placed on the true floor of the cave because of the amount of fallen rock from the ceiling.

Practices not permitted to be used by this study included use of bolts or anchors to affix sensors, removal of accumulated rock dust from flat surfaces in the cave before sensor placement, and exposure of fresh, unweathered rock faces for sensor placement. The use of non-modified rock cave surfaces for sensor placement during the vibration trials may have affected the resolution of the various sensors used.

Quality Assurance of Vibration and Accelerometer Data

Maximum vertical velocity data recorded during the vibration trials indicated that the geophones with lighter elements (the R.T. Clark geophones) were more sensitive to vibration intensities induced by the experimental conditions than were the geophones designed to record higher energy levels (the Instantel geophones). The maximum vertical velocities recorded by the lighter element R.T. Clark geophones were about 10 times or less than the smallest maximum vertical velocities recorded by the Instantel geophones (tables 1 and 2).

After examination of the waveform files for the Instantel geophones, the determination was that these geophones, which are designed for monitoring blasting (high energy) work, did not receive enough excitation from the construction equipment to register usable data. The signal-to-noise ratio in the cave was not sufficient to move the heavier sensor elements of the Instantel geophones compared to the lighter sensor elements of the R.T. Clark geophones, as indicated by the lack of difference in response among all vibration trials in the higher energy Instantel geophone data (table 2).

The hammer drill, plate compactor, jackhammer, and accelerometers used for the vibration trials were electrically powered through alternating current (AC) line power brought in from outside the cave. Activation of the construction equipment produced localized power surges that caused sharp spikes of erroneous voltage data immediately before the vibration from the construction equipment reached the AC-powered accelerometer sensors. To account for the erroneous voltage data, accelerometer data in the time window between their activation and the arrival of the vibrations from the construction equipment were not recorded. The vibration recording equipment and sensors were battery powered and those data were not affected by AC voltage spikes. Maximum vertical and horizontal acceleration data for each trial are included in table 3.

Table 1. Maximum velocity values from the R.T. Clark geophones for vibration source trials at Mammoth Cave National Park, March 2016.

[Color in parentheses is from figure 4; in/s, inch per second]

Source	Geophone 1 (red)			Geophone 2 (green)			Geophone 3 (blue)		
	Transverse velocity (in/s)	Longitudinal velocity (in/s)	Vertical velocity (in/s)	Transverse velocity (in/s)	Longitudinal velocity (in/s)	Vertical velocity (in/s)	Transverse velocity (in/s)	Longitudinal velocity (in/s)	Vertical velocity (in/s)
Hammer drill at location 1	0.0000940	0.0000902	0.000116	0.0003930	0.000465	0.000783	0.0000610	0.0000598	0.0000706
Plate compactor at location 1	0.0000863	0.0000801	0.000098	0.000126	0.000548	0.000119	0.000192	0.000156	0.0000746
Plate compactor at location 2	0.0000722	0.0000791	0.0000539	0.0000923	0.000323	0.000144	0.000133	0.000106	0.0000512
Jackhammer at location 1	0.0000380	0.0000406	0.000126	0.0000406	0.000117	0.0000525	0.0000414	0.0000376	0.0000367
Jackhammer at location 2	0.0000428	0.0000471	0.0000939	0.0000541	0.000101	0.0000754	0.0000415	0.0000431	0.0000392
Simulated bat survey	0.0000384	0.0000398	0.0000624	0.000109	0.000793	0.000232	0.0000775	0.0000715	0.0000779
Ambient vibration	0.0000346	0.0000353	0.0000359	0.0000359	0.0000572	0.0000548	0.0000345	0.0000363	0.0000333

Source	Geophone 4 (white)			Geophone 5 (pink)			Geophone 6 (orange)		
	Transverse velocity (in/s)	Longitudinal velocity (in/s)	Vertical velocity (in/s)	Transverse velocity (in/s)	Longitudinal velocity (in/s)	Vertical velocity (in/s)	Transverse velocity (in/s)	Longitudinal velocity (in/s)	Vertical velocity (in/s)
Hammer drill	0.0000458	0.0000368	0.0000709	0.0000527	0.0001103	0.0000836	0.0000545	0.0000654	0.0000432
Plate compactor at location 1	0.000160	0.000130	0.000150	0.000859	0.00226	0.000947	0.000213	0.000158	0.000104
Plate compactor at location 2	0.000135	0.000114	0.000109	0.000405	0.000707	0.000313	0.000176	0.000177	0.0000827
Jackhammer at location 1	0.0000428	0.0000415	0.0000533	0.000144	0.000431	0.000173	0.0000630	0.0000483	0.0000393
Jackhammer at location 2	0.0000422	0.0000439	0.0000667	0.0000807	0.0001620	0.0001274	0.0000721	0.0001272	0.0000464
Simulated bat survey	0.0002111	0.0002845	0.0004508	0.0002053	0.0004011	0.0003952	0.0001085	0.0000990	0.0001045
Ambient vibration	0.0000450	0.0000354	0.0000515	0.0000438	0.0000405	0.0000616	0.0000512	0.0000457	0.0000495

Table 2. Maximum velocity values from the Instantel geophones for vibration source trials at Mammoth Cave National Park, March 2016.

[in/s, inch per second]

Source	Instantel geophone A			Instantel geophone B		
	Transverse velocity (in/s)	Longitudinal velocity (in/s)	Vertical velocity (in/s)	Transverse velocity (in/s)	Longitudinal velocity (in/s)	Vertical velocity (in/s)
Hammer drill at location 1	0.0133	0.0025	0.0140	0.0022	0.0040	0.0016
Plate compactor at location 1	0.0130	0.0028	0.0140	0.0019	0.0040	0.0012
Plate compactor at location 2	0.0130	0.0025	0.0143	0.0022	0.0040	0.0016
Jackhammer at location 1	0.0130	0.0025	0.0140	0.0022	0.0037	0.0012
Jackhammer at location 2	0.0130	0.0025	0.0140	0.0022	0.0037	0.0016
Simulated bat survey	0.0130	0.0022	0.0140	0.0022	0.0037	0.0016
Ambient vibration	0.0133	0.0025	0.0140	0.0022	0.0037	0.0016

Table 3. Vertical and horizontal acceleration values from the accelerometers for vibration source trials at Mammoth Cave National Park, March 2016.

[in/s^2, inch per square second]

Source	Vertical acceleration (in/s^2)	Horizontal acceleration (in/s^2)
Hammer drill at location 1	0.252	0.152
Plate compactor at location 1	0.130	0.178
Plate compactor at location 2	0.222	0.330
Jackhammer at location 1	0.035	0.062
Jackhammer at location 2	0.153	0.136
Simulated bat survey	0.340	0.339
Ambient vibration	0.039	0.066

Vibration Monitoring Results near a Bat Hibernaculum

Acceleration values during the vibration source trials ranged from 0.035 inch per square second (in/s^2) for a jackhammer at location 1 to 0.34 in/s^2 for a simulated bat survey. All trials recorded acceleration values less than a literature value of 0.394 in/s^2 reported as an approximate threshold for human perception (fig. 5; Parsons and Griffin, 1988). Maximum vertical and horizontal acceleration results collected during the various vibration source trials are shown in table 3. Acceleration values during the ambient vibration trial were approximately 10 percent greater than the maximum acceleration value recorded during the jackhammer at location 1 trial (fig. 5). Using the jackhammer at location 1 necessitated a halt to construction activities whereas for ambient vibration trial recordings, construction activities proceeded as normal. Other manual construction activities that did not involve the jackhammer or plate compactor were not halted and may have contributed to acceleration values recorded during monitoring of the ambient vibration trial. All maximum acceleration values recorded by this study were less than 0.394 in/s^2 reported by Parsons and Griffin (1988) as an approximate threshold for human perception of acceleration.

Maximum vertical velocity values recorded for each vibration source trial by the R.T. Clark geophones ranged from 0.000062 in/s (ambient vibration) to 0.000947 in/s (plate compactor at location 1) and were at least 100 times less than values reported in the literature as potentially affecting hibernating bats and detectable by humans or mice (fig. 6 and table 1). Limited studies of construction-related vibration effects on hibernation of Indiana bats indicated that limiting peak vibrations induced by activity to 0.1–0.25 in/s was likely to reduce disturbance to hibernating bats (Delaney, 2002). Carman and others (2007) identified background vibration levels in their laboratory setting of 0.028 in/s and vibration levels that produced visible agitation in mice of 0.1 in/s (fig. 6). Human perception of vibration was reported to begin at a velocity as small as 0.02 in/s (American Association of State Highway and Transportation Officials, 2004). Vibration was reported to become disturbing to human perception at about 0.1–0.2 in/s (American Association of State Highway and Transportation Officials, 2004; Wiss, 1981).

The velocity and acceleration results shown in figures 7A–7G and figure 8, respectively, indicate the maximum values measured by each R.T. Clark geophone with different vibration source trials. Maximum vibration velocities measured in these trials ranged from a vertical velocity of 0.0000333 in/s at geophone 3 during the ambient vibration trial (fig. 7G) to a longitudinal velocity of 0.00226 in/s at geophone 5 during the plate compactor trial at location 1 (table 1, figs. 7B and 7G). Acceleration values ranged from 0.035 in/s^2 in the vertical component during the jackhammer at location 1 trial to 0.34 in/s^2 in the vertical component during the simulated bat survey (table 3 and fig. 8). The maximum ambient vibration velocity was a vertical velocity of about 0.0000616 in/s (table 1, fig. 7G) and was similar to the median of vertical velocity values (0.00006 in/s) during the jackhammer trials at locations 1 and 2 (table 1). Using the jackhammer necessitated a halt to construction activities whereas for ambient recordings, construction activities were not halted and may have continued during data collection.

The maximum values recorded were 0.00226 in/s of longitudinal velocity and 0.34 in/s^2 of vertical acceleration (tables 1 and 3). For all vibration source trials, vertical velocity and acceleration values were smaller than published values perceptible by humans or that produced visible agitation in laboratory mice (figs. 5 and 6; Parsons and Griffin, 1988; Carman and others, 2007).

Published studies of perceptible vibration values used to compare results from this work only contained values of vertical velocity or vertical acceleration. Additional data about the bat species in the hibernaculum, including resonant frequency of the bats and the frequency of bat echolocation signals, could improve the choice of seismic sensors and frequency ranges to monitor in future studies. Norton and others (2011) identified in a laboratory setting how differences in the resonant frequency of human legs of about 20 Hz from that of mouse legs of about 60 Hz made the mouse legs more vulnerable to vibration disturbance from jackhammering that had larger vibration levels at the 60 Hz frequency. Similar knowledge of bat resonant frequency and echolocation frequency could improve identification of which construction vibration frequencies had the greatest potential to induce disturbances to bats or their navigation.

An interdisciplinary approach that incorporated biological assessment techniques before, during, and after could have enhanced interpretation of results from this study. For example, a biological assessment of the condition of bats in the hibernaculum before, during, and after the vibration exposure could help identify which vibration source parameters were most disturbing to the bats. A more detailed identification of differences among components of the vibration sources, including motion, magnitude, frequency, bandwidth, and periodicity, could contribute to that evaluation.

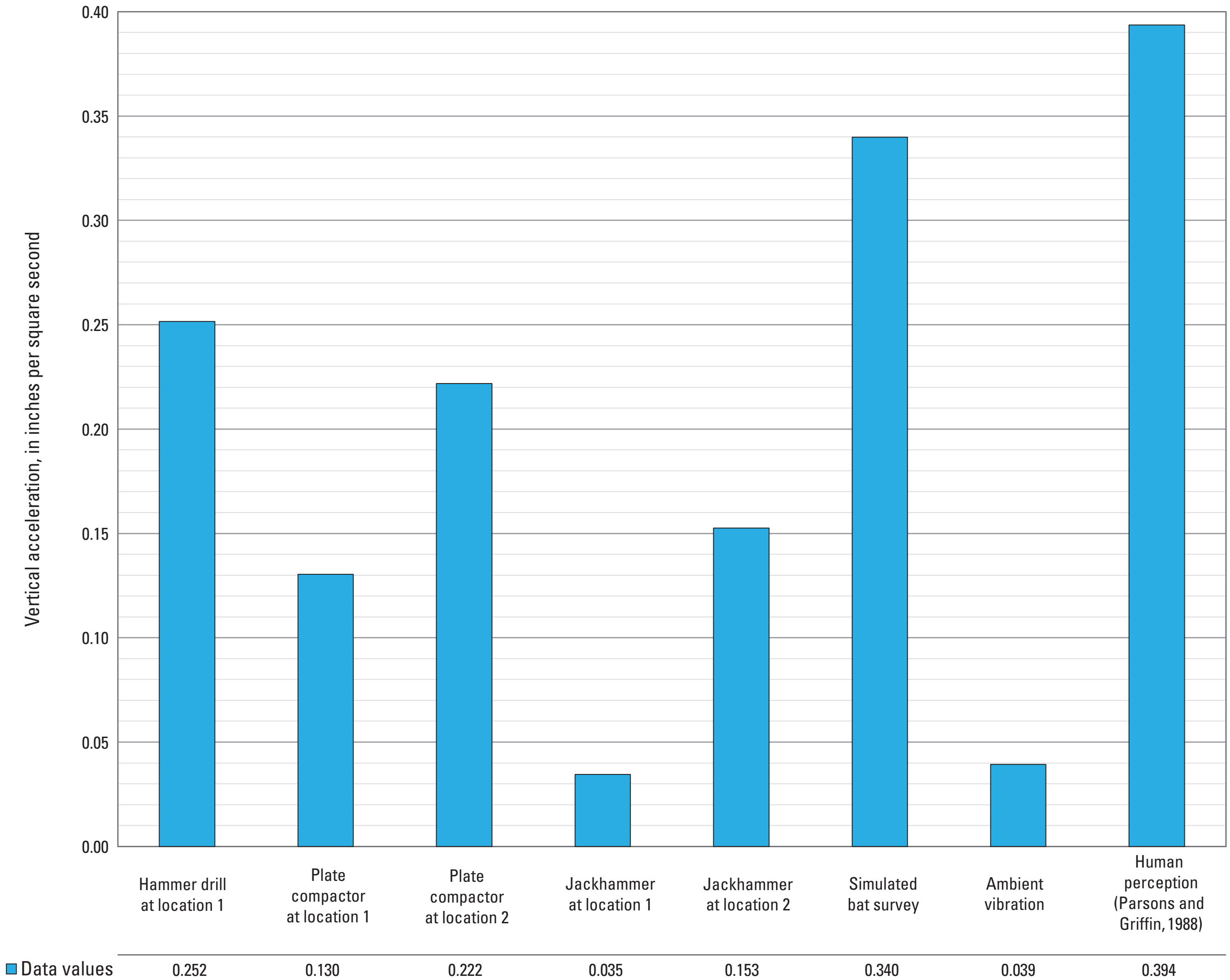


Figure 5. Comparison of the maximum vertical acceleration for each of the seven vibration sources to values from literature. Approximate human perception values from Parsons and Griffin (1988). Vibration source from location 1 unless otherwise noted.

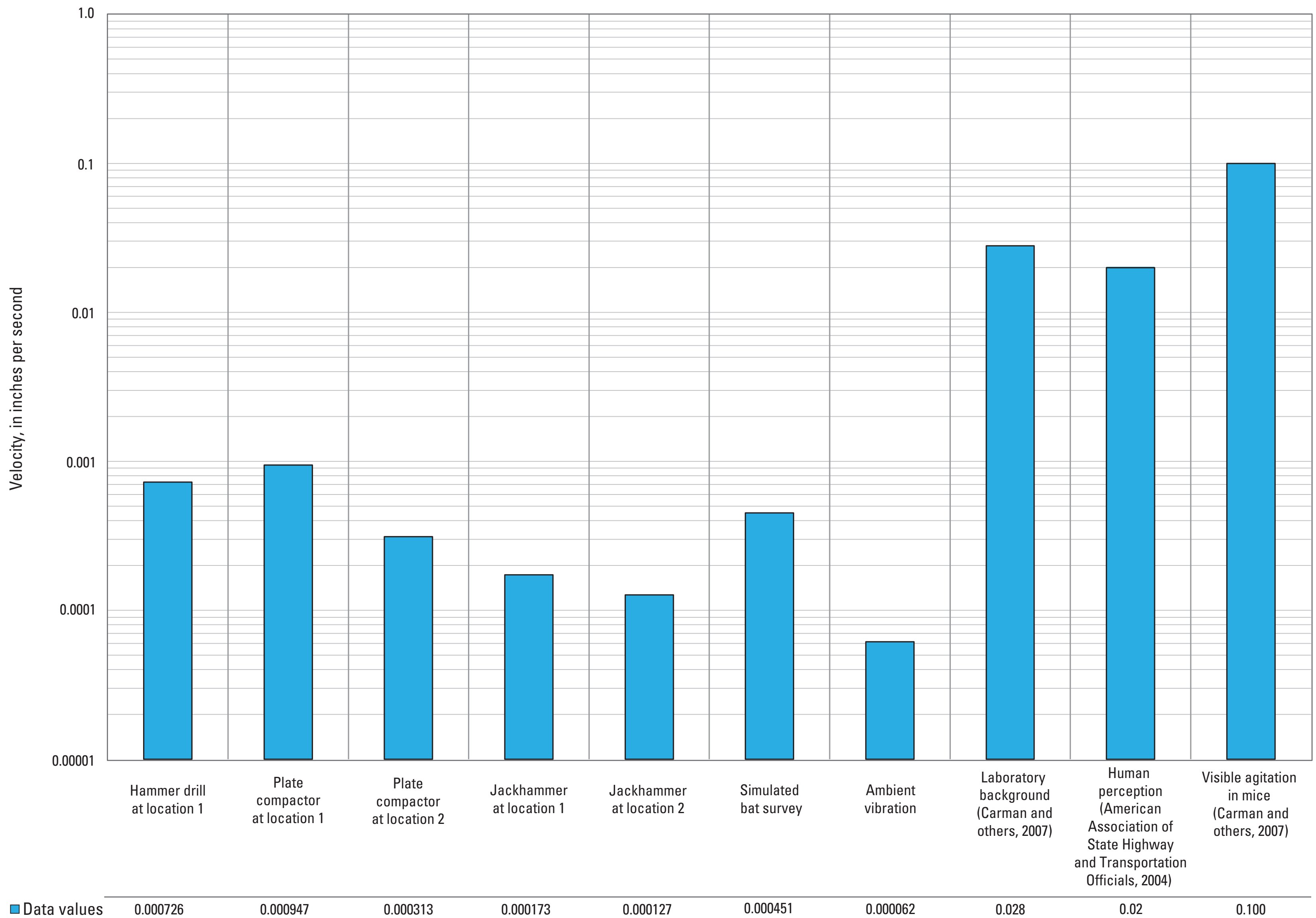


Figure 6. Comparison of the maximum vertical velocity recorded on the six R.T. Clark geophones for each of the seven vibration sources evaluated by this study to values from literature. Vertical velocity values reported for laboratory background and that produced visible agitation in mice during laboratory trials were from Carman and others (2007). Vertical velocity values at the limit of human perception were from American Association of State Highway and Transportation Officials (2004). Vibration source from location 1 unless otherwise noted.

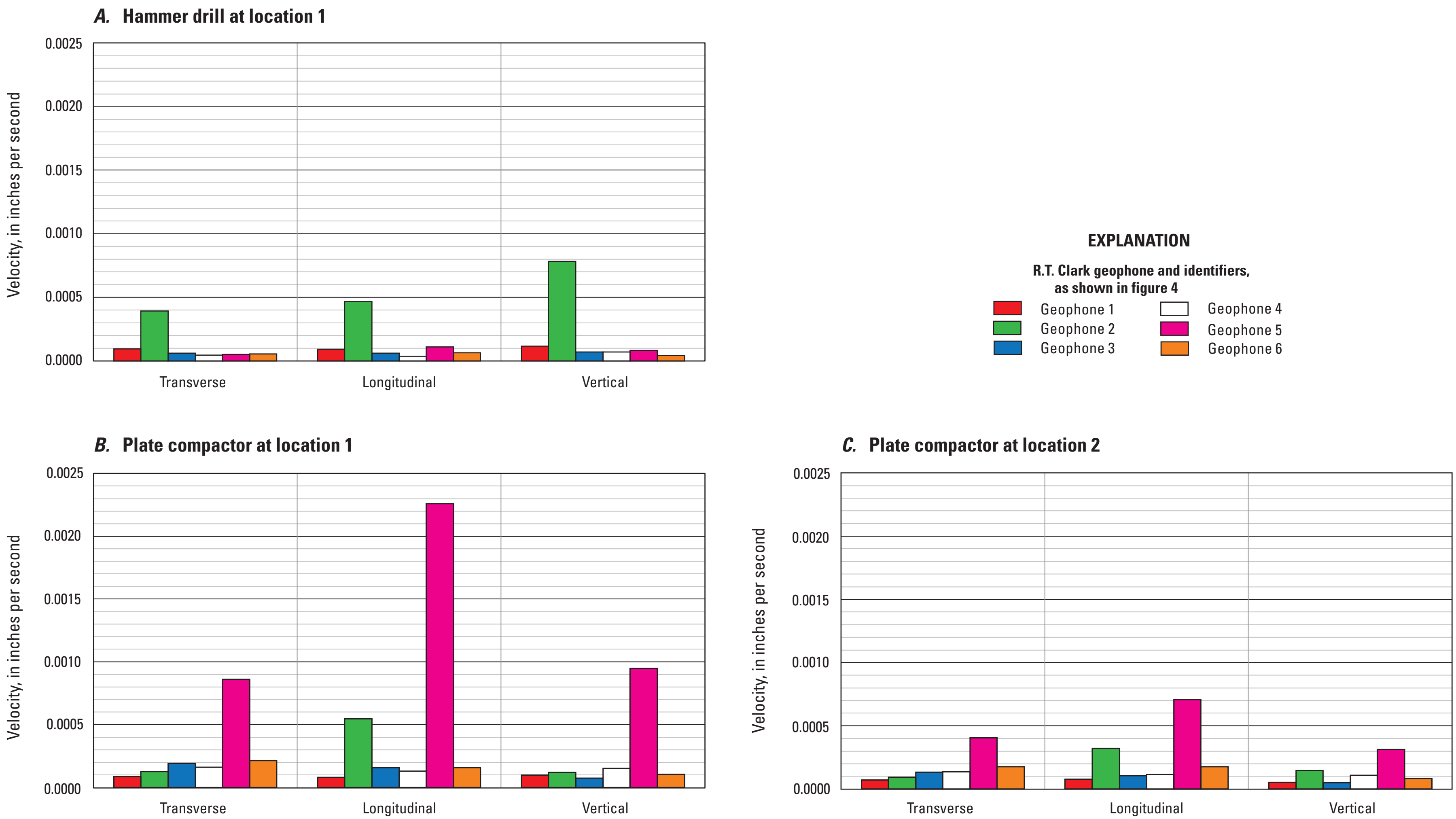


Figure 7. Distribution of maximum velocity across the six R.T. Clark geophones for the seven vibration sources evaluated by this study. *A*, hammer drill at location 1; *B*, plate compactor at location 1; *C*, plate compactor at location 2; *D*, jackhammer at location 1; *E*, jackhammer at location 2; *F*, simulated bat survey; *G*, ambient vibration. Each geophone has three entries per graph, one for each component—transverse, longitudinal, and vertical.

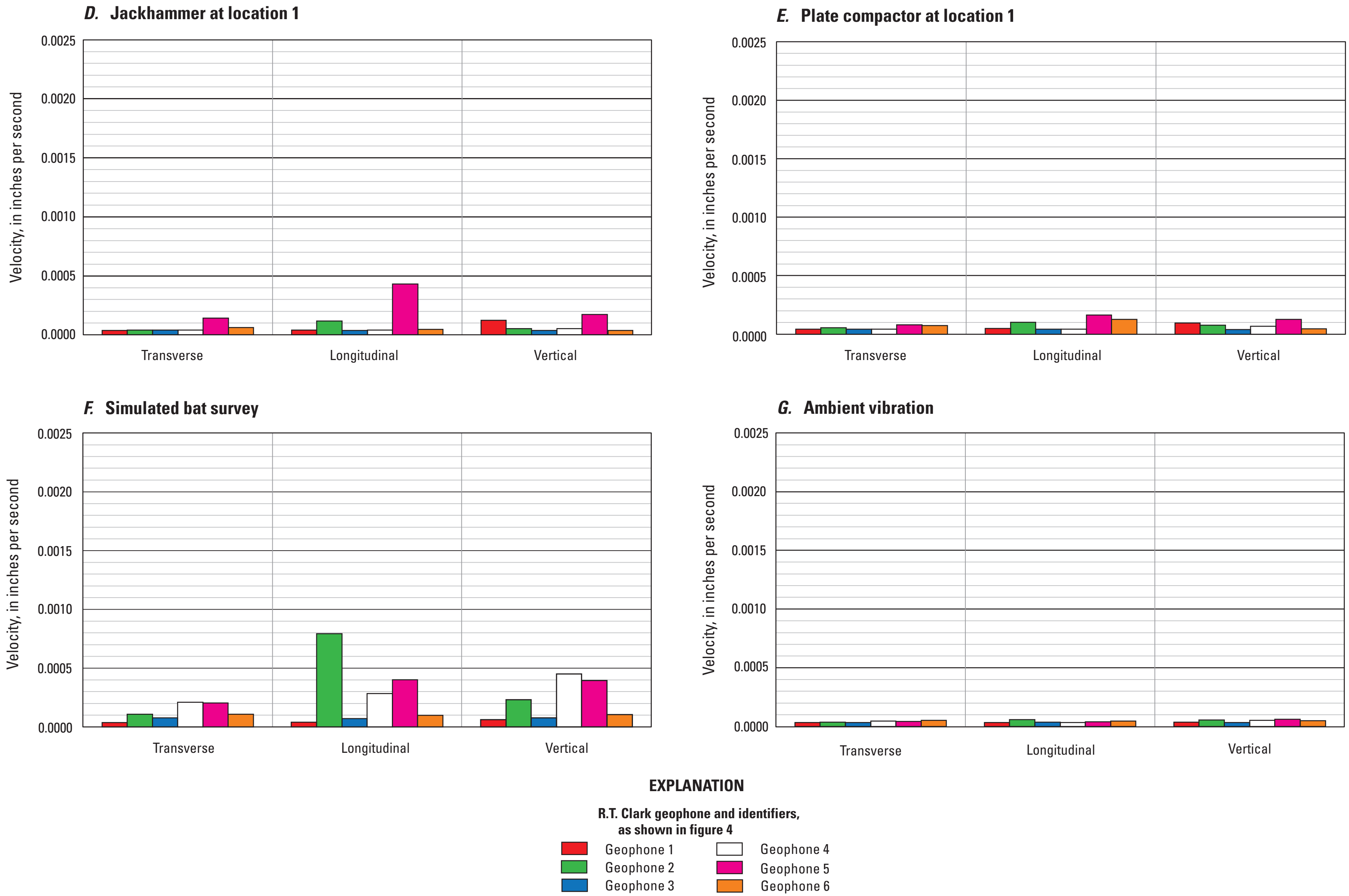
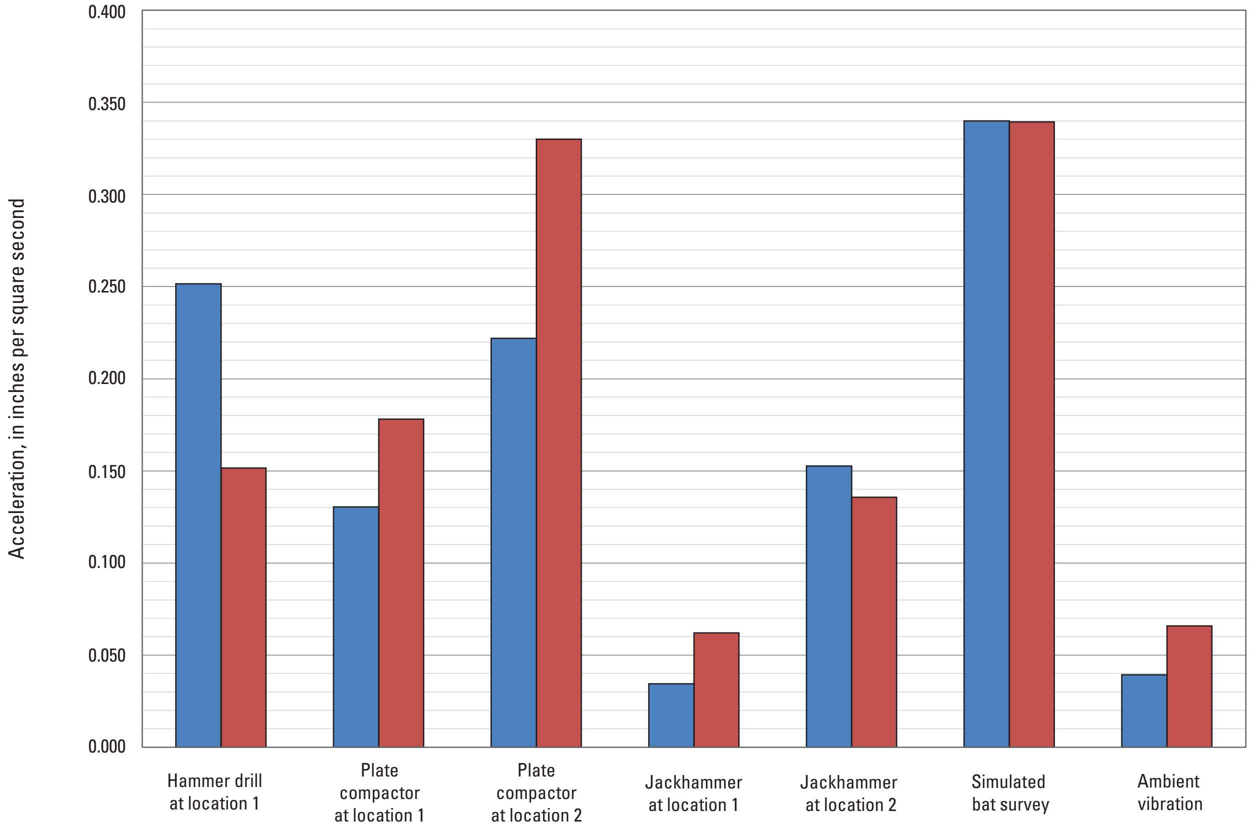


Figure 7. Distribution of maximum velocity across the six R.T. Clark geophones for the seven vibration sources evaluated by this study. *A*, hammer drill at location 1; *B*, plate compactor at location 1; *C*, plate compactor at location 2; *D*, jackhammer at location 1; *E*, jackhammer at location 2; *F*, simulated bat survey; *G*, ambient vibration. Each geophone has three entries per graph, one for each component—transverse, longitudinal, and vertical.—Continued



Data values	Hammer drill at location 1	Plate compactor at location 1	Plate compactor at location 2	Jackhammer at location 1	Jackhammer at location 2	Simulated bat survey	Ambient vibration
Vertical	0.252	0.130	0.222	0.035	0.153	0.340	0.039
Horizontal	0.152	0.178	0.330	0.062	0.136	0.339	0.066

Figure 8. Comparison of maximum acceleration values in the vertical and horizontal components for the seven vibration sources evaluated by this study. Vibration source from location 1 unless otherwise noted.

Summary

In March of 2016, U.S. Geological Survey scientists recorded construction and other vibrations in a bat hibernaculum beneath Mammoth Cave National Park to determine if the vibrations were disturbing the hibernating bats. Data were collected using geophones and accelerometers placed throughout the cave. The seven sources of vibration that were recorded include hammer drill (one location), plate compactor (two locations), jackhammer (two locations), personnel simulating a bat survey near the hibernaculum (walking throughout the cave), and ambient background levels. Vibrations were measured for approximately 8–10 seconds during each triggering of the source and each source was recorded 5–10 times to represent the reproducibility of the vibrations.

Acceleration values during the vibration source trials ranged from 0.035 inch per square second (in/s^2) from a jackhammer at location 1 to 0.34 in/s^2 for a simulated bat survey. All trials recorded acceleration values less than a literature value of 0.394 in/s^2 reported as a threshold for human perception of acceleration.

Vertical velocity values ranged from 0.000062 inch per second (in/s) (ambient vibration) to 0.000947 in/s (plate compactor at location 1) and were at least 100 times less than values reported in the literature as potentially affecting hibernating bats and detectable by humans or mice. Maximum vibration velocities measured in these trials ranged from a vertical velocity of 0.0000333 in/s at geophone 3 during the ambient vibration trial to a longitudinal velocity of 0.00226 in/s at geophone 5 during the plate compactor trial at location 1. The maximum vertical acceleration value recorded was 0.34 in/s^2. For all experiments, vertical velocity and acceleration values (published studies only contained values of vertical velocity/acceleration) were smaller than published values perceptible by humans or that produced animal agitation.

References Cited

Adams, R.F., Morrow, W.S., and Koebel, C.M., 2018, Vibration monitoring data from a bat hibernaculum at Mammoth Cave National Park, Kentucky, March 2016: U.S. Geological Survey data release, at https://doi.org/10.5066/P94LHZHR.

American Association of State Highway and Transportation Officials, 2004, Standard recommended practice for evaluation of transportation related earthborne vibrations, R8–96, standard specifications for transportation materials and methods of sampling and testing, part I, specifications: Washington, D.C., American Association of State Highway and Transportation Officials, 2004).

Carman, R.A., Quimby, F.W., and Glickman, G.M., 2007, The effect of vibration on pregnant laboratory mice: Proceedings: 36th International Congress and Exhibition on Noise Control Engineering (INTER-NOISE 2007 ISTANBUL; Turkish Acoustical Society). August 28–31, 2007, Istanbul, Turkey, p. 3767–3776.

Çelebi, Mehmet, 2000, Seismic instrumentation of buildings: U.S. Geological Survey, Open-File Report 2000–157, 37 p., accessed June 1, 2016, at https://pubs.usgs.gov/of/2000/0157/.

Delaney, D.K., 2002, Prioritization of threatened and endangered species sound research on army installations: U.S. Army Engineer Research and Development Center, U.S. Army Corps of Engineers, Publication ERDC/CERL TR–02–30, 79 p.

Geopsy Project, 2016, Geopsy.org packages, release 2.10.1, win32: accessed June 1, 2016, at https://geopsy.org.

Kalkan, E., Banga, K., Ulusoy, H.S., Fletcher, J.P.B, Leith, W.S., Reza, S., and Cheng, T., 2012, Advanced earthquake monitoring system for U.S. Department of Veterans Affairs medical buildings—Instrumentation: U.S. Geological Survey Open-File Report 2012–1241, 143 p., accessed June 1, 2016, at https://pubs.usgs.gov/of/2012/1241/.

King, K.W., Carver, D.L., and Worley, D.M., 1988, Vibration investigation of the museum building at White Sands National Monument, New Mexico: U.S. Geological Survey Open-File Report 88–544, 19 p., accessed June 1, 2016, at https://pubs.er.usgs.gov/publication/ofr88544.

Norton, J.N., Kinard, W.L., and Reynolds, R.P., 2011, Comparative vibration levels perceived among species in a laboratory animal facility: Journal of the American Association for Laboratory Animal Science, v. 50, no. 5, p. 653–659.

Palmer, A.N., 1981, A geological guide to Mammoth Cave National Park: Teaneck, N.J., Zephyrus Press, 196 p.

Parsons, K.C., and Griffin, M.J., 1988, Whole-body vibration perception thresholds: Journal of Sound Vibration, v. 121, p. 237–258.

Snyder, J.M., Treuting, P.M., Brabb, Thea, Miller, K.E., Covey, Ellen, and Lencioni, K.L., 2015, Hepatic lipidosis in a research colony of big brown bats (*Eptesicus fuscus*): Comparative Medicine, v. 65, no. 2, p. 133–139.

United Nations Educational, Scientific and Cultural Organization, 2017, World Heritage List: Mammoth Cave National Park web page, accessed January 15, 2017, at http://whc.unesco.org/en/list/150/.

Wiss, J.F., 1981, Construction vibrations—State-of-the-art: American Society of Civil Engineers Journal of the Geotechnical Division, v. 107, no. GT2, p. 167–181.

For additional information contact:
Director, Ohio-Kentucky-Indiana Water Science Center
U.S. Geological Survey
9818 Bluegrass Parkway
Louisville, Kentucky 40299-1906
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