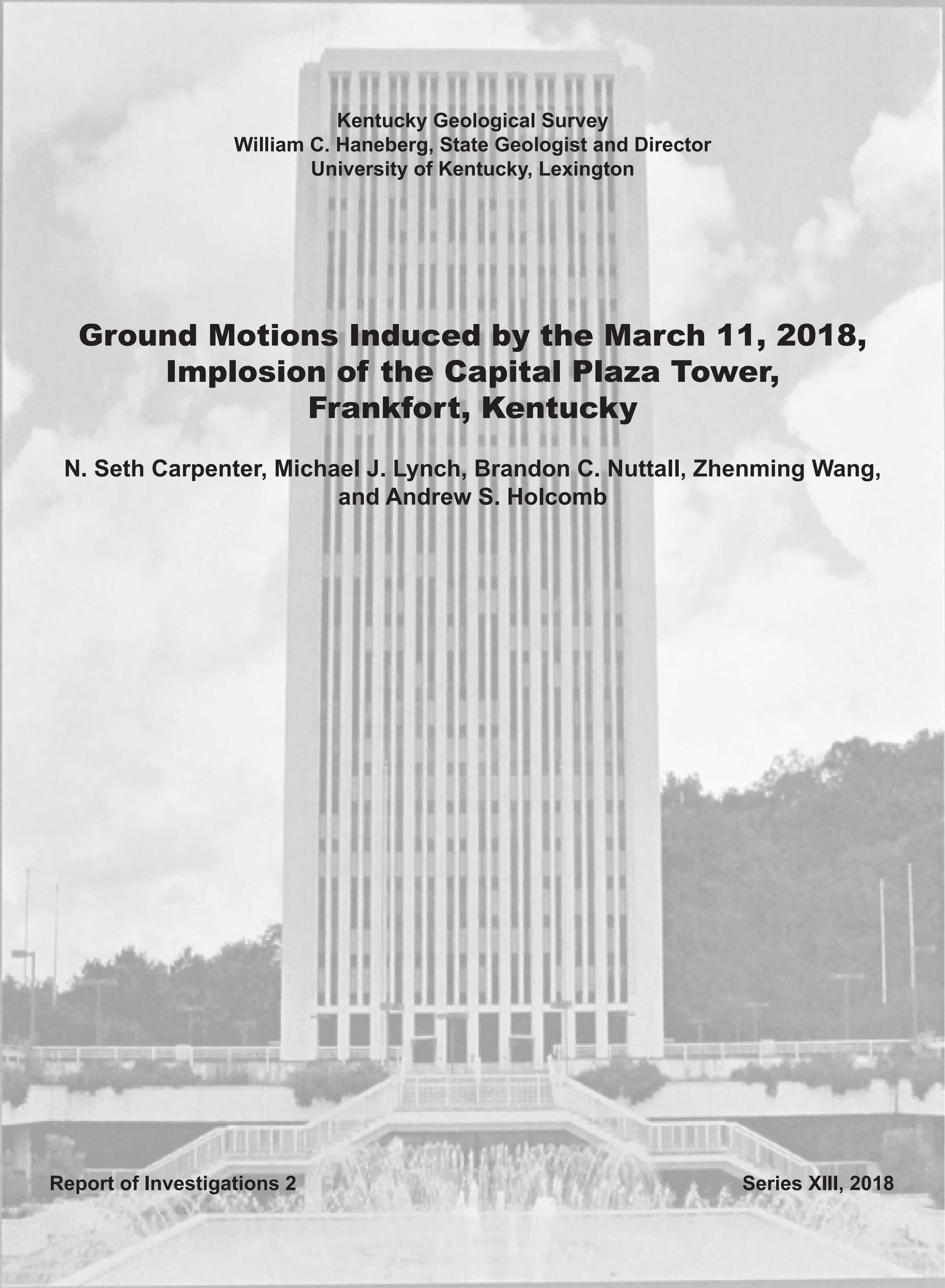

Kentucky Geological Survey
William C. Haneberg, State Geologist and Director
University of Kentucky, Lexington

Ground Motions Induced by the March 11, 2018, Implosion of the Capital Plaza Tower, Frankfort, Kentucky

N. Seth Carpenter, Michael J. Lynch, Brandon C. Nuttall, Zhenming Wang, and Andrew S. Holcomb

Report of Investigations 2

Series XIII, 2018

Kentucky Geological Survey
University of Kentucky, Lexington

Ground Motions Induced By the March 11, 2018, Implosion Of the Capital Plaza Tower, Frankfort, Kentucky

N. Seth Carpenter, Michael J. Lynch, Brandon C. Nuttall, Zhenming Wang, and Andrew S. Holcomb

Report of Investigations 2 https://doi.org/10.13023/kgs.ri02.13 Series XIII, 2018

Our Mission

The Kentucky Geological Survey is a state-supported research center and public resource within the University of Kentucky. Our mission is to support sustainable prosperity of the commonwealth, the vitality of its flagship university, and the welfare of its people. We do this by conducting research and providing unbiased information about geologic resources, environmental issues, and natural hazards affecting Kentucky.

Earth Resources—Our Common Wealth

www.uky.edu/kgs

© 2018
University of Kentucky
For further information contact:
Technology Transfer Officer
Kentucky Geological Survey
228 Mining and Mineral Resources Building
University of Kentucky
Lexington, KY 40506-0107

Technical Level

General | Intermediate | Technical

Statement of Benefit to Kentucky

This report demonstrates that ground-motion recordings, made on different types of underlying geology, using scheduled, human-caused events as a seismic source, can provide useful information to the public about levels of shaking (or ground motion), related safety concerns, locations susceptible to increased shaking in the event of an earthquake.

ISSN 0075-5591

Contents

Abstract....1
Introduction and Setting....1
Geologic Setting....2
Ground-Motion Monitoring....2
Results and Discussion....4
  Implosion....4
  Ground Motions....5
Interpretation....8
Summary....9
Data and Resources....10
Acknowledgments....10
References Cited....11

Figures

1. General geologic map of Frankfort, Ky. 3
2. Photograph of instrumentation at station CPT3....4
3. Graph showing amplitude responses from input ground acceleration for the instruments used at each site....5
4. A. Photograph of final detonation and the nearly simultaneous initiation of the collapse of the Capital Plaza Tower. B. Photograph of the tower above the ground floor impacting the ground to induce the strongest shaking recorded....5
5. Graph of ground-motion time history recorded at CPT3....6
6. Ground-velocity and acceleration time histories of the Capital Plaza Tower collapse....6
7. Ground-velocity recordings by seismographs deployed by the Explosives and Blasting Branch....7
8. Amplitude spectra of the velocity time histories from Figure 6....8
9. Ratios of each horizontal component's amplitude spectrum to that of the vertical component for each KGS site....9
10. Photographs of Capital Plaza Tower from the location of station CPT1 shortly before the implosion and shortly after the building's demolition....10

Tables

1. Instrument locations and types....4
2. Peak ground motions and intensities....7

Ground Motions Induced By the March 11, 2018, Implosion Of the Capital Plaza Tower, Frankfort, Kentucky

N. Seth Carpenter, Michael J. Lynch, Brandon C. Nuttall, Zhenming Wang, and Andrew S. Holcomb

Abstract

The demolition by implosion of the Capital Plaza Tower in downtown Frankfort provided an opportunity to record seismic waves from a known source of seismic energy in order to observe local ground-motion amplification and resonance within the underlying unconsolidated sediment. The Kentucky Geological Survey deployed three strong-motion accelerographs at approximately equal distances around the tower to record ground motions induced by its collapse. The KGS instruments were installed at sites with different underlying geology: one on bedrock and two on Kentucky River Valley unconsolidated sediments.

Using images captured by a high-speed video camera, with timing synchronized with the clock of one of the strong-motion accelerographs, the sequence of ground-motion-inducing events from the tower demolition (blast explosions and the collapsing tower's impact with the ground) was identified in the ground-motion time histories recorded at the rock site. This allowed the ground motions from the tower collapse recorded at all stations deployed for the event to be isolated and analyzed. The ground motions from the tower collapse recorded at the observation sites were weak and were likely imperceptible to humans. The detected motions, which had modified Mercalli intensities of only I to II at the rock and soil sites, respectively, were unlikely to have caused any damage there.

Seismic-wave resonance within the Kentucky River Valley sediment was identified from the analysis of these recordings. The resonance frequencies were similar at all KGS soil sites, and also were similar to those observed on seismographs deployed by the Energy and Environment Cabinet's Explosives and Blasting Branch. These observations indicate that in the unlikely event of a nearby strong earthquake, shaking is expected to be amplified within the unconsolidated Kentucky River Valley sediments underlying downtown Frankfort.

Introduction and Setting

The 388-ft-tall, 28-story Capital Plaza Tower was the tallest building in Frankfort and the third-tallest in Kentucky at the time of its opening in 1972. Problems with maintenance and operation of the aging tower led to it being closed in 2016, and it was demolished by implosion on March 11, 2018. This scheduled demolition presented an opportunity to record seismic waves in the alluvium and colluvial materials in the Kentucky River Valley of downtown Frankfort. Simultaneously recording seismic waves from the same source of seismic energy, in this case the implosion, on sites in the river valley and on adjacent hard rock allowed an estimation of the amplification that could be expected on soil sites from stronger shaking from an actual earthquake. The recordings also allowed the resonance frequencies in sediment underlying downtown Frankfort to be determined.

The Kentucky Geological Survey deployed strong-motion accelerographs at three monitoring sites next to the tower with different underlying geology. During the weeks before the implosion, we contacted a homeowner who lives across the Kentucky River from the tower, the owner of a business in downtown Frankfort, and state Finance Cabinet officials to secure permission to place the instruments on their properties, all at similar distances from the tower. We also agreed to share the resulting data with the Finance Cabinet. A high-speed video camera was set up at one of the monitoring sites to correlate implosion events with the seismic recordings and help with their interpretation.

Geologic Setting

Frankfort is located between Louisville and Lexington in the Bluegrass physiographic region of Kentucky along the Kentucky River, at what was historically a river crossing along a buffalo trace (Wilson, 1931). The river eroded through Upper Ordovician carbonate units (Cressman, 1973; Cressman and Noger, 1976; McLaughlin and others, 2008; Clepper and others, 2011), and the valley bottom is filled with Quaternary alluvium and colluvial material (Fig. 1). As the river evolved, abundant fracturing and associated karst controlled meandering and abandonment of existing channels (Andrews, 2006). Downtown Frankfort is developed within active and abandoned river channels, and lies mostly on silt- and clay-rich fluvial material with minor amounts of locally derived sand and gravel (Moore, 1975); it is underlain by the Tyrone Limestone or members of the Lexington Limestone at normal stream pool level.

Unconsolidated-sediment thicknesses and seismic-wave velocities are the key parameters that control seismic-wave amplification and resonance. Thickness of alluvium and colluvial materials in the vicinity of the Capital Plaza Tower, and near the KGS's monitoring sites (Fig. 1), range from 0 m at soil-bedrock outcrop contacts to 22 m at a boring next to the Kentucky Transportation Cabinet building, approximately 130 m southeast of the Capital Plaza Tower (S&ME, 2012; William M. Andrews Jr., Kentucky Geological Survey, personal communication, March 21, 2018). Seismic stations CPT1 and CPT2 are located on top of Kentucky River Valley sediments, and both are in the same valley as the current, active channel of the Kentucky River. But because the stations are different distances from bedrock outcrops and other river channels—Benson Creek at CPT1 and an abandoned Kentucky River channel at CPT2 (Andrews, 2006)—they overlie sediments of potentially different thickness and type. Seismic station CPT3 is located directly on bedrock from the lower part of the Lexington Limestone.

Ground-Motion Monitoring

Table 1 gives the instrument locations, which were at horizontal distances of 404 to 432 m from the center of the Capital Plaza Tower, prior to its demolition, and at variable azimuths. All sites were instrumented with strong-motion accelerographs, each of which was oriented to record motions in the vertical, horizontal radial (away from and toward the tower), and horizontal transverse (perpendicular to radial) directions. Bags with 50 to 100 lb of sand were placed on top of the strong-motion accelerographs to enhance the sensors' coupling with the ground, and to prevent differential motion between the accelerograph and the ground in the event of strong shaking (Fig. 2).

The strong-motion accelerographs digitized ground motions with 24-bit resolution at 200 samples per second, and were equipped with GPS receivers that provide absolute Coordinated Universal Time with an accuracy of $\pm 5 \times 10^{-6}$ s. These instruments are capable of recording on-scale ground accelerations of 1g (the acceleration due to gravity) at CPT1 and 2g at CPT2 and CPT3. As shown in Figure 3, the accelerometers in the strong-motion accelerographs have frequency-independent responses to ground accelerations from 0 Hz to frequencies higher than those of typical engineering interest: 50 Hz at CPT2 and 200 Hz at CPT1 and CPT3. These instruments were recently calibrated (January 2014, February 2018, and February 2018

Figure 1. General geology of Frankfort, Ky. Red triangles show locations where ground-motion recordings from the implosion of the Capital Plaza Tower (white star) were collected by KGS instruments. Stations deployed by the Energy and Environment Cabinet's Explosives and Blasting Branch are shown as blue triangles. Inset shows the locations of all four KGS stations.

for CPT1, CPT2, and CPT3, respectively), ensuring the accuracy of the absolute ground-motion measurements.

An additional station, CPT0, was established 4.0 km to the northeast, along the same azimuth as CPT1. This station was instrumented with a broadband seismograph capable of recording weak ground motion across a broad range of frequencies, with a flat response to ground velocity at frequencies from 0.025 to 85 Hz (Fig. 3). This station was used to observe weaker ground motions at a location with low cultural noise levels, and at a greater distance from the tower, to allow body waves to separate from surface waves, because of their differences in travel time. The analysis of the recordings from CPT0 is not included in this report.

The broadband seismograph at CPT0 recorded continuously from its installation five days before the implosion until its removal two days after the event. The strong-motion accelerographs were configured to begin acquisition when triggered by either a specified ground-motion level being exceeded or manually by an external trigger, whichever occurred first. CPT1 and CPT3 were triggered manually and CPT2 was triggered by the specified ground-motion level being exceeded.

The recordings of the tower's collapse by each component of each strong-motion accelerograph were isolated from the full recordings by identify-

Table 1. Instrument locations and types. Back azimuth is from site to Capital Plaza Tower, measured in degrees from geographic north. Corner frequency: sensors reliably record ground motions for frequencies less than f_c.

Site	*Latitude (°N)*	*Longitude (°E)*	*Elevation (km)*	*Distance (m) to Tower*	*Back Azimuth (°)*	*Instrument Type*	*Sensor Corner Frequency (f_c (Hz))*
CPT0	38.23502	–84.900340	219	4,069	150	broadband seismometer	85
CPT1	38.206718	–84.879391	157	432	150	2g accelerometer	200
CPT2	38.200266	–84.879453	158	404	33	2g accelerometer	50
CPT3	38.202010	–84.872440	161	423	290	1g accelerometer	200

ing when the collapse began in the video footage captured by the high-speed video camera at CPT1. The isolated waveforms, which did not include the initiating blast detonations, were 20 s long, beginning at the collapse onset time. These waveforms were processed with Seismic Analysis Code software to yield physical ground motions, using the following steps:

1. Linear trends were removed from the isolated waveforms.
2. The beginnings and ends of the detrended time series were tapered, using a 5 percent Tukey window.
3. A Butterworth bandpass filter with corner frequencies of 0.5 Hz and 99 Hz was applied.
4. The calibrated instrument response was deconvolved to yield ground acceleration.
5. A final Butterworth bandpass filter with corner frequencies of 0.5 and 50 Hz was applied to remove signal differences due to the different sensors used (Table 1) and to focus on observations within the frequency band typically of engineering interest.

A team from the Energy and Environment Cabinet's Explosives and Blasting Branch also deployed seismographs to monitor ground motions from the demolition. The recordings from two of their stations were made available to KGS (Ralph King, Energy and Environment Cabinet, personal communication, March 18, 2018).

Results and Discussion

Implosion

The Capital Tower Plaza was demolished through a sequence of at least 10 explosive detonations, noted as D1 to D10. Figure 4 shows the final detonation (D10) and subsequent collapse of the tower. Downward displacement began with D10, which removed support from the southeast side of the foundation or ground floor. Energy from the initiation of the collapse generated seismic waves that were observed at all recording stations. As the

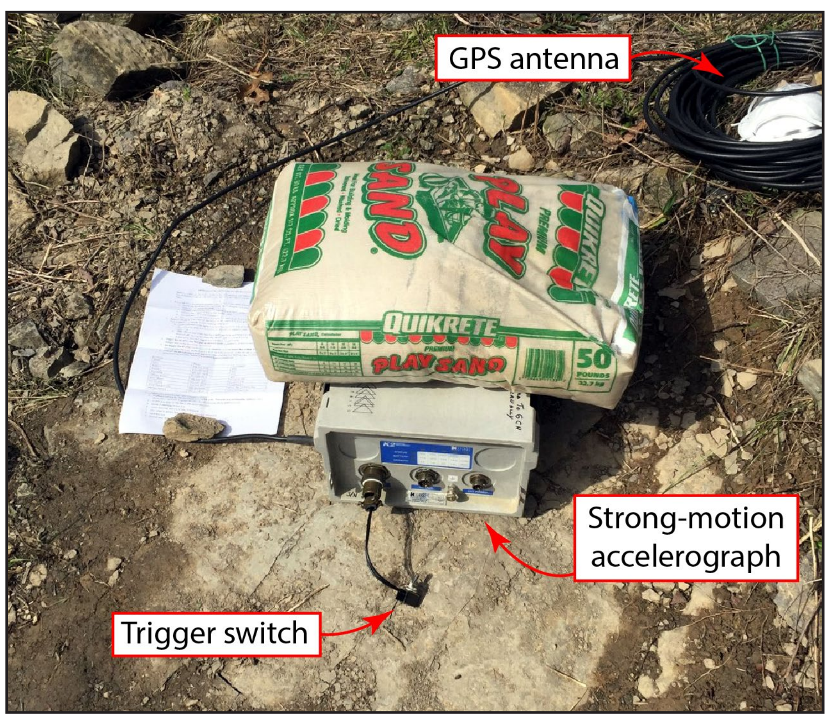

Figure 2. Instrumentation at station CPT3. Photo by Zhenming Wang.

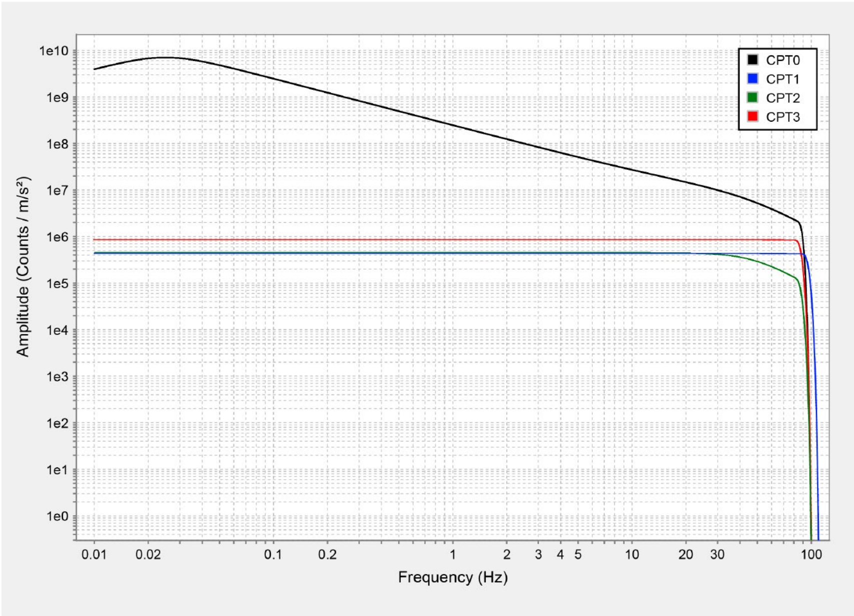

Figure 3. Amplitude responses from input ground acceleration for the instruments used at each site. Differences between the responses of each orthogonal component for a particular instrument are indistinguishable on this plot, and only the vertical-component frequency responses are shown.

ground-floor or foundation gave way, which lasted just over 1 s, the remainder of the tower impacted the ground over approximately 6 s, which induced the largest observed ground motions.

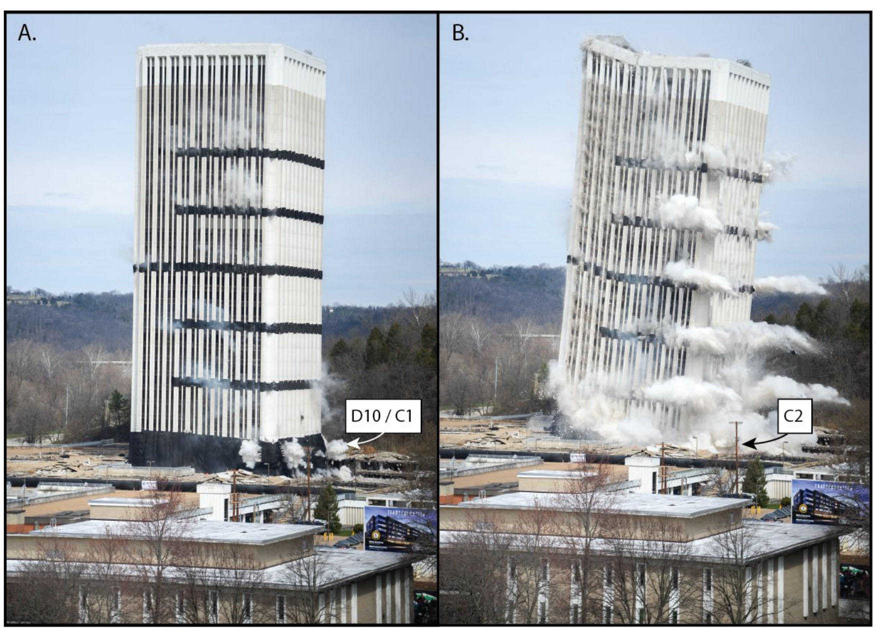

Figure 4. A. Final detonation (D10) and the nearly simultaneous initiation of the collapse of the Capital Plaza Tower (C1). B. The tower above the ground floor impacts the ground (C2) to induce the strongest shaking recorded. Photos courtesy Hannah Brown, © 2018 *The State Journal;* reproduced with permission.

All three strong-motion accelerographs recorded the entire demolition process, from the first detonation through the entirety of the collapse of the tower. The recordings also captured reflected or trapped waves within the Kentucky River Valley sediments. Figure 5 shows the ground-motion time series recorded at CPT3, annotated with the major events of the demolition.

Ground Motions

Time histories of the ground motions induced by the tower collapse recorded by each strong-motion accelerograph are shown in Figure 6 and the peak ground-motion levels are given in Table 2. The peak velocities (in inches per second to be consistent with the Explosives and Blasting Branch's recordings and regulations) and accelerations recorded at the soil sites exceeded those recorded by the corresponding components at the rock site: 0.027 in./s and 0.029 in./s were observed at soil sites CPT1 and CPT2, respectively, and 0.009 in./s was observed at rock site CPT3.

Modified Mercalli intensities were calculated from the observed peak velocities for each site (Table 2) using a scale developed for eastern North America (Kaka and Atkinson, 2004). At both soil sites, the modified Mercalli intensities were II for all components, and at the rock site, the intensities were I for all components. Modified Mercalli intensity is an approximate measure of the severity of shaking from seismic waves in terms of typical experiences by humans and how the built environment responds. Intensities of I and II are very low and are associated

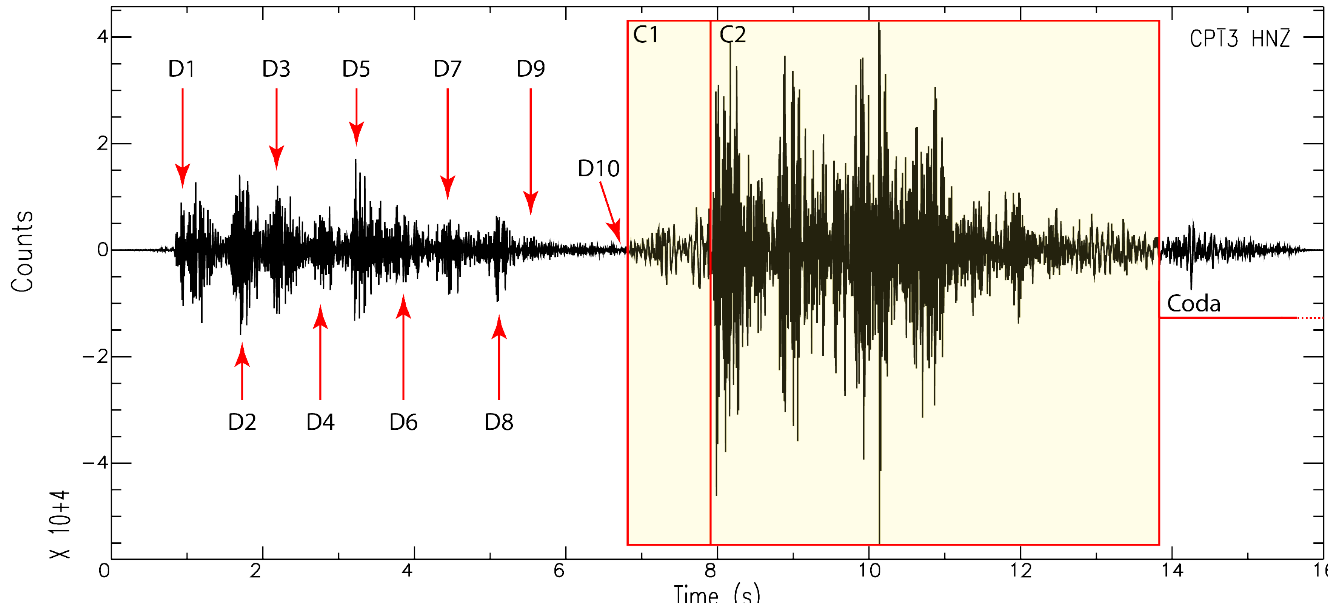

Figure 5. Ground-motion time history recorded at CPT3. The ground motions from the blast detonations in or under the Capital Plaza Tower are labeled sequentially (D1–D10), and the seismic wave arrivals from the collapse of the tower are highlighted in yellow. The collapse began (C1) with the final detonation (D10) and the nearly simultaneous collapse of the southeastern side of the tower's foundation or ground floor; collapse event C2 includes the prolonged impact of the collapse of the remainder of the tower. The coda—the series of scattered waves arriving after the primary arrivals—is composed of reflected seismic waves and is not related to direct seismic arrivals.

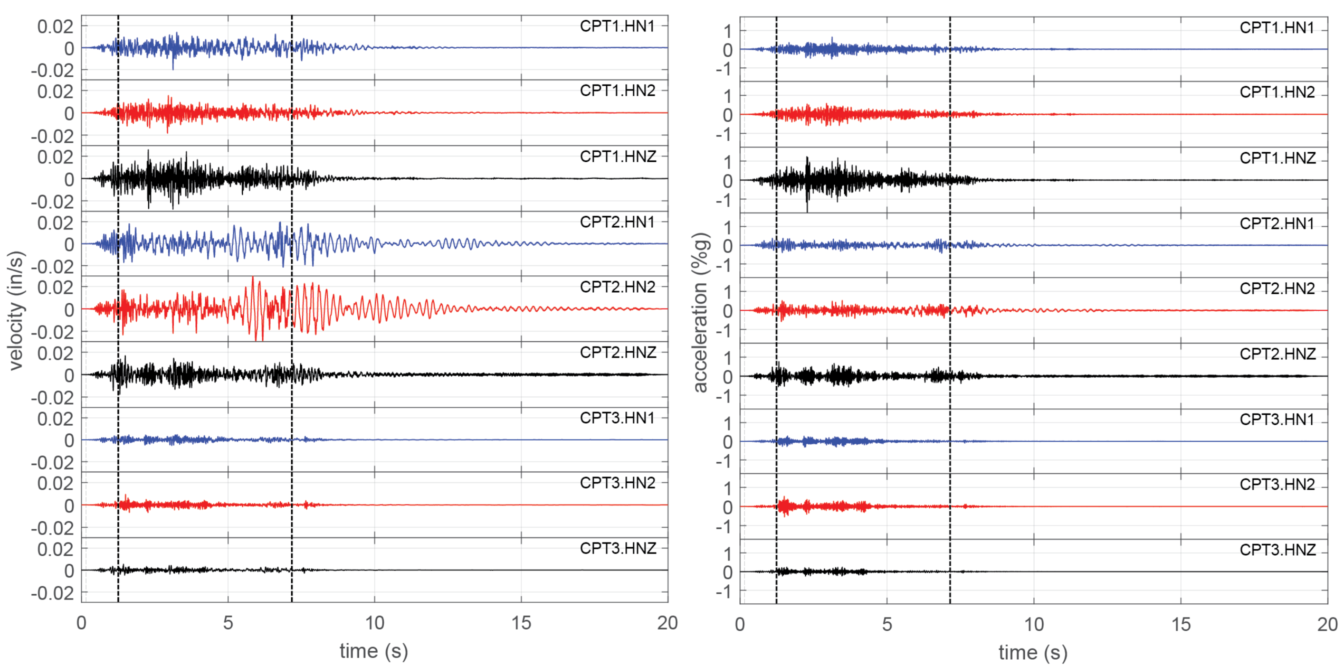

Figure 6. Ground-velocity (left) and acceleration (right) time histories of the Capital Plaza Tower collapse (preceding detonations not included). The same vertical scale is used for each trace. Traces are labeled by station name and component (HN1 = radial, HN2 = transverse, HNZ = vertical). The vertical dashed lines delineate the C1 and C2 time periods shown in Figure 5.

Table 2. Peak ground motions and intensities. HNZ is vertical component, HN1 is radial component, HN2 is transverse component. Modified Mercalli intensity scale is calculated using the relationship in Kaka and Atkinson (2004).

Component	*Peak Ground Velocity (in./s)*	*Peak Ground Acceleration (%g)*	*Modified Mercalli Intensity*
CPT1.HNZ	0.020	0.649	II
CPT1.HN1	0.018	0.615	II
CPT1.HN2	0.027	1.726	II
CPT2.HNZ	0.021	0.427	II
CPT2.HN1	0.029	0.584	II
CPT2.HN2	0.018	0.770	II
CPT3.HNZ	0.005	0.306	I
CPT3.HN1	0.009	0.549	I
CPT3.HN2	0.005	0.246	I

with the following experiences (from pubs.usgs.gov/gip/earthq4/severitygip.html; last accessed 03/22/2018):

I. Not felt except by a very few under especially favorable conditions.

II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

These low intensities indicate that shaking from the event was not likely felt by people, and damage to the built environment was unlikely at the distances of the KGS recordings stations.

Recordings from Explosives and Blasting Branch stations PINK and AME are shown in Figure 7. Ground motions from the explosives are apparently captured in these recordings (absolute timing is unavailable), as well as ground motions from the tower collapse. Because the Explosives and Blasting Branch sites, which are also on Kentucky River Valley sediment, were significantly closer to the tower, the peak velocities they recorded were expected to be higher than those from the KGS stations, and this was in fact the case: 0.078 in./s and 0.075 in./s were recorded on the radial components at the PINK station (203 m from the tower) and AME station (293 m from the tower), respectively.

The signal durations (the length of time the ground motions exceed background ambient noise levels) recorded on all three components at both KGS soil sites, CPT1 and CPT2, and at the Explosives and Blasting Branch sites, which are also on soil, exceeded the signal durations observed on rock on the corresponding components. This indi-

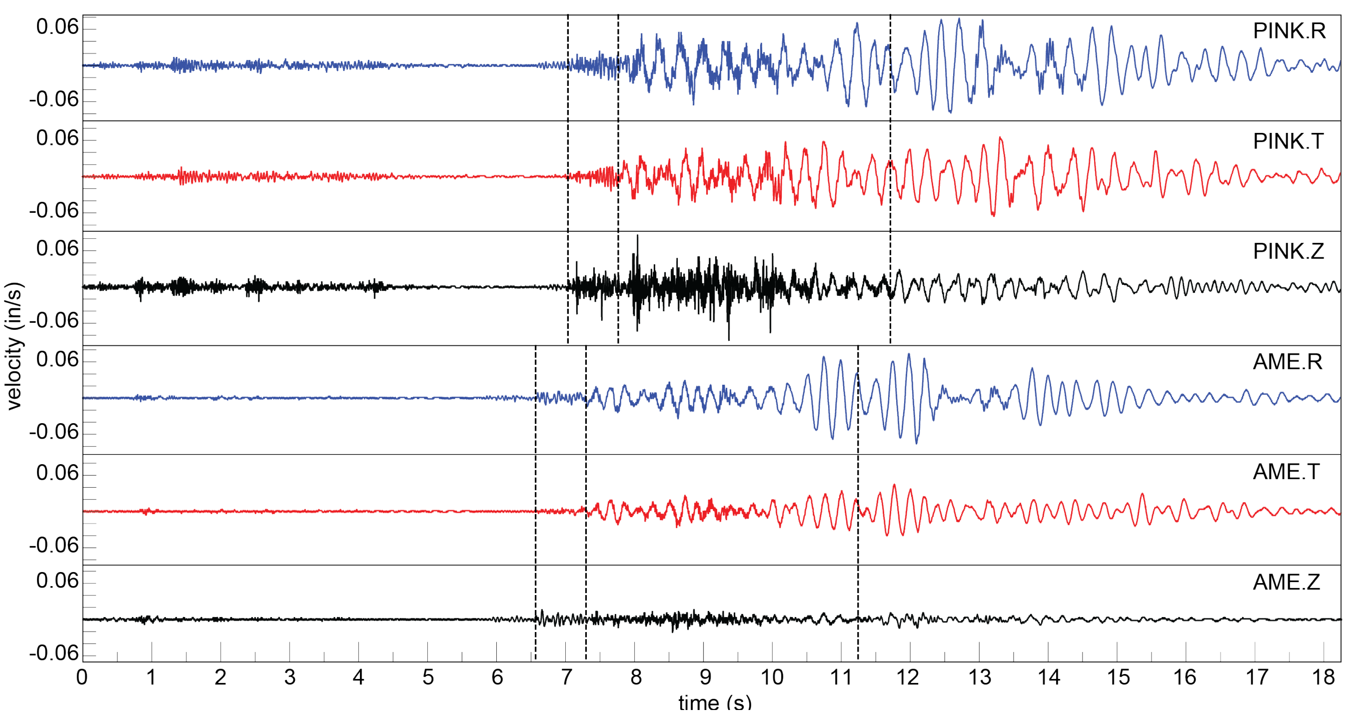

Figure 7. Ground-velocity recordings by seismographs deployed by the Explosives and Blasting Branch (Fig. 1). The same vertical scale is used for each trace. The vertical dashed lines approximately delineate the C1 and C2 time periods shown in Figure 5.

cates that seismic waves were trapped within the Kentucky River Valley sediments, and that their reflections continued to propagate after the collapse was over.

Interpretation

Although each strong-motion accelerograph was approximately the same distance away from the Capital Plaza Tower, the ground motions recorded at each site differ: ground velocities and ground accelerations were higher at the soil sites than at the rock site. Some of the differences may be due to differences in the forces imparted into the ground in different directions by the collapsing tower. Figure 4 indicates that the tower tilted during the collapse, which would enhance radial accelerations along azimuths parallel to the direction of the tilt. CPT3 is almost exactly along such an azimuth, and CPT1's back azimuth is subparallel to it. This directional dependence of the input energy would also increase transverse accelerations at sites perpendicular to the direction of the tilt; CPT2 is almost exactly along such an azimuth. Therefore, in combination with other complexities in the collapse, the horizontal components of the forces imparted into the ground varied with direction.

A detailed assessment of the physics of the collapse is beyond the scope of this report. However, the transverse component recorded larger ground motions than the radial component at CPT2, as would be expected for directionally variable imparted forces. In contrast, peak ground-motion values in the radial direction were slightly reduced at both CPT1 and CPT3 compared to the transverse direction, which is inconsistent with the anticipated azimuthal dependence of the imparted forces.

The conflicting observations at CPT1, CPT2, and CPT3 with regard to expected effects of the complex energy source (i.e., the collapsed building) indicate that the directional dependence of the imparted forces probably is not the main reason for the differences in observed ground motions. The major differences, which are made clearer by the amplitude spectra of the ground-velocity time histories shown in Figure 8, correlate with the geology underlying the different sites. In particular, and as previously stated, ground motions are larger at the soil sites than at the rock sites.

The increase in ground-motion levels at soil sites compared to rock sites is called site effect; it is a well-known effect, and has been documented

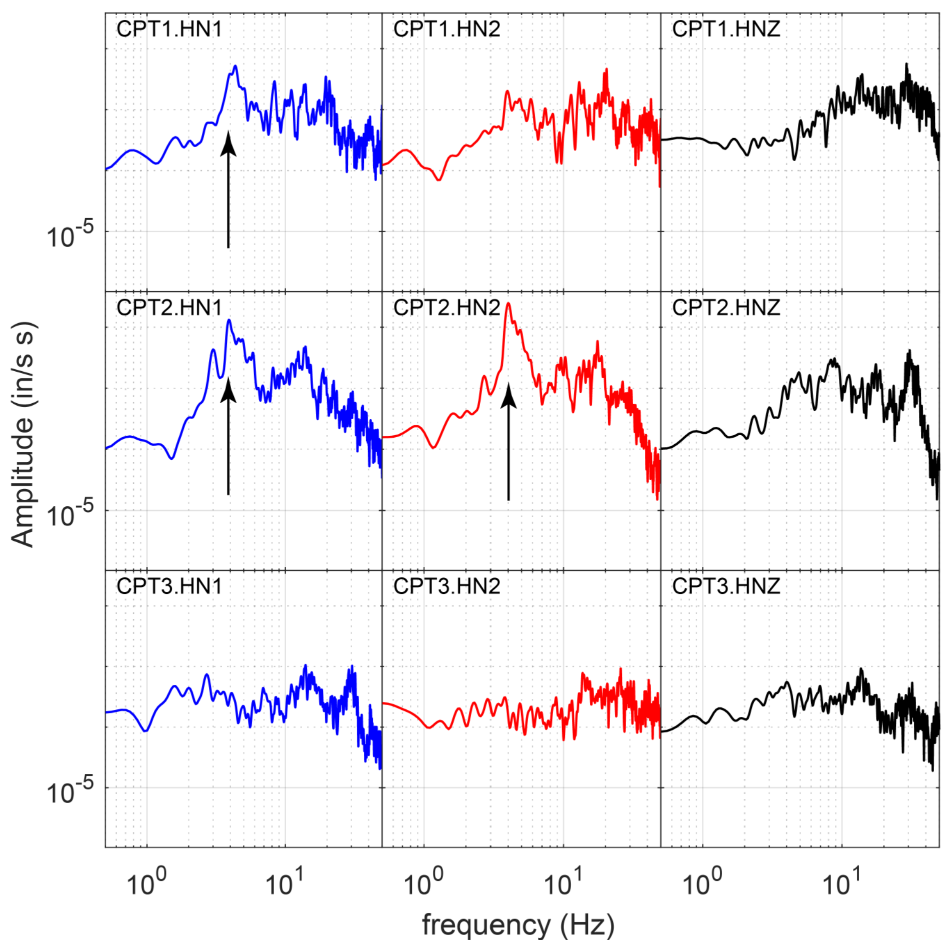

Figure 8. Amplitude spectra of the velocity time histories from Figure 6. The predominant peaks, indicated by arrows on the velocity spectra, at soil sites CPT1 and CPT2 are evidence of seismic-wave resonance in the underlying soils. Spectral plots are labeled by station name and component (HN1 = radial, HN2 = transverse, HNZ = vertical).

in many areas underlain by unconsolidated sediments (Seed and others, 1988; Woolery and others, 2008; Carpenter and others, 2018), and can result from several factors. Peaks in the amplitude spectra (Fig. 8) occur at nearly identical frequencies at CPT1 and CPT2. These peaks are the result of seismic waves that propagate from the underlying rocks into the overlying soil layers beneath each station, and from waves that become trapped and resonate within the soil layers. In the downtown Frankfort area, the Kentucky River Valley sediments are apparently susceptible to site effect.

Figure 9 shows the resonant peaks more clearly through spectral ratios. For each site, each horizontal component's amplitude spectra was divided by that of the vertical component. In this way, differences in wave propagation paths between the sites instrumented with strong-motion accelerographs and some of the complexities of the physics of the tower collapse are effectively removed, and the results are approximations of the empirical site responses, or measurements of site effect at these locations. These plots reveal resonance peaks of 4.5 and 4.0 Hz at soil sites CPT1 and CPT2, respectively. Also, the spectral ratios for CPT3 indicate that there was only minor amplification at this rock site, which is expected for sites lacking underlying soil layers. Although digital data were not available from the Explosives and Blasting Branch stations, the predominant frequencies at each site were estimated from the transverse-component seismograms shown in Figure 7: 3.7 Hz at the PINK site and 4.8 Hz at AME.

Summary

The demolition of the Capital Plaza Tower changed the skyline of Frankfort forever (Fig. 10) and provided a unique opportunity to observe seismic waves from a known energy source in the downtown Frankfort area. The Kentucky Geological Survey deployed three strong-motion accelerographs at approximately equal distances around the tower to record ground motions induced by the tower's collapse. The KGS instruments were installed at sites with different underlying geology: one on bedrock and two on Kentucky River Valley sediment.

Using images captured by a high-speed video camera, with timing synchronized with the clock of one of the strong-motion accelerographs, the sequence of ground-motion-inducing events from the demolition—blast explosions and the impact of the collapsing tower with the ground—was identified in the ground-motion time histories recorded at the rock site. The ground motions from the tower collapse were weak at the observation sites, and

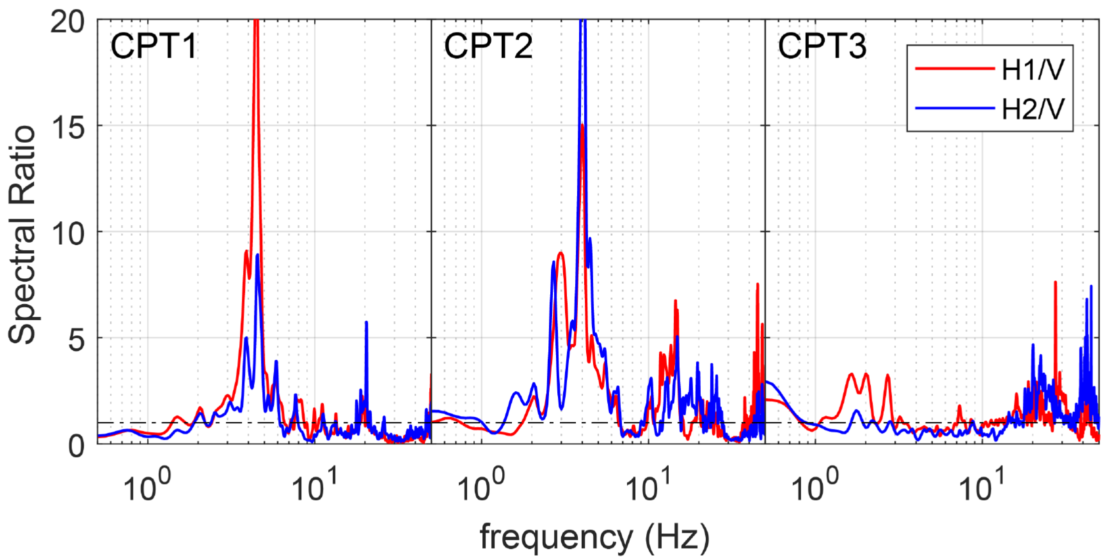

Figure 9. Ratios of each horizontal component's amplitude spectrum to that of the vertical component (HV) for each KGS site. The dash-dotted horizontal line corresponds to a ratio of 1.0. HV ratios have been used to quantify site response (i.e., site effect) in other settings.

Figure 10. (Left) Capital Plaza Tower from the location of station CPT1 shortly before the implosion. (Right) The same view, shortly after the building's demolition, with a student observer next to the instrument. Photos by Seth Carpenter.

were likely imperceptible to humans and unlikely to have caused any damage at these locations, having modified Mercalli intensities of I to II.

The frequency spectra of the time histories were analyzed and seismic-wave resonance within the Kentucky River Valley sediment was identified. The resonance frequencies were similar at all KGS soil sites—4.5 and 4.0 Hz at CPT1 and CPT2, respectively—and also were similar to those observed on seismographs deployed by the Explosives and Blasting Branch, which were also on soil. This suggests that the response of the valley sediments to seismic waves could be observed on the recordings gathered during the demolition. This also suggests that in the event of a nearby strong earthquake, shaking would be expected to be amplified in downtown Frankfort.

Data and Resources

Instrumentation used for this project is part of the Kentucky Seismic and Strong-Motion Network, a joint endeavor by the Kentucky Geological Survey and the University of Kentucky Department of Earth and Environmental Sciences since 1982 (doi: http://dx.doi.org/10.7914/SN/KY). Recordings of the Capital Plaza Tower demolition from these instruments are available for download from www.uky.edu/KGS/geologichazards/data.htm (last accessed March 2018). Plots of recordings from the Explosives and Blasting Branch were provided by Ralph King of the Energy and Environment Cabinet.

Acknowledgments

We would like acknowledge and thank landowners who allowed KGS to install seismic instruments on their property for this project: Nancy Hamilton and Doyle Devers, whose family farm hosted CPT0; Mary Dee Boemker, whose home hosted CPT1; Will and Michael Harrod, whose business hosted CPT2; and the Finance Cabinet, which allowed KGS to install CPT3 behind the Transportation Cabinet Building. We also thank Josh Calnan and the Explosives Research Team in the Department of Mining Engineering at the University of Kentucky for the use of their high-speed video camera. Hannah Brown of *The State Journal* provided photographs of the demolition.

References Cited

Andrews, W.M., Jr., 2006, Geologic controls on Plio-Pleistocene drainage evolution of the Kentucky River in central Kentucky: Kentucky Geological Survey, ser. 12, Thesis 4, 216 p.

Carpenter, N.S., Wang, Z., Woolery, E.W., and Rong, M., 2018, Estimating site response with recordings from deep boreholes and HVSR: Examples from the Mississippi Embayment of the central United States: Bulletin of the Seismological Society of America, 11 p., DOI: 10.1785/0120170156.

Clepper, M., Ettensohn, F.R., Nuttall, B.C., and Smath, R.A., 2011, New approaches to understanding the Upper Ordovician Lexington Limestone in the Bluegrass Region of central Kentucky (guidebook for Kentucky Society of Professional Geologists fall field trip, Sept. 24, 2011): Kentucky Society of Professional Geologists, 41 p.

Cressman, E.R., 1973, Lithostratigraphy and depositional environments of the Lexington Limestone (Ordovician) of central Kentucky: U.S. Geological Survey Professional Paper 768, 61 p.

Cressman, E.R., and Noger, M.C., 1976, Tidal-flat carbonate environments in the High Bridge Group (Middle Ordovician) of central Kentucky: Kentucky Geological Survey, ser. 10, Report of Investigations 18, 21 p.

Kaka, S.I., and Atkinson, G.M., 2004, Relationships between instrumental ground-motion parameters and modified Mercalli intensity in eastern North America: Bulletin of the Seismological Society of America, v. 94, no. 5, p. 1728–1736.

McLaughlin, P.I., Brett, C.E., Holland, S.M., and Storrs, G.W., eds., 2008, Stratigraphic renaissance in the Cincinnati Arch: Implications for Upper Ordovician paleontology and paleoecology: Cincinnati, Ohio, Cincinnati Museum Center Scientific Contributions, v. 2, 280 p.

Moore, F.B., 1975, Geologic map of the Frankfort West quadrangle, Franklin and Anderson Counties, Kentucky: U.S. Geological Survey Geologic Quadrangle Map GQ-1221, scale 1:24,000.

S&ME, 2012, Final report of geotechnical exploration, Capital Plaza Parking Garage and Office Building: Frankfort, Ky., S&ME Project No. 1831-11-430, 72 p., finance.ky.gov/services/statebuilding/Documents/2017/Capitol%20Plaza%20Tower%20RFP%20Built%20to%20Suit/Capital%20Plaza%20Final%20Geo%20Report.pdf [accessed 03/20/2018].

Seed, H.B., Romo, M.P., Sun, J.I., Jaime, A., and Lysmer, J., 1988, The Mexico earthquake of September 19, 1985—Relationship between soil conditions and earthquake ground motions: Earthquake Spectra, v. 4, p. 687–729.

Wilson, S.M., 1931, Leestown—Its founders and its history: Register of Kentucky State Historical Society, v. 29, p. 385–396.

Woolery, E.W., Lin, T.L., Wang, Z., and Shi, B., 2008, The role of local soil-induced amplification in the 27 July 1980 northeastern Kentucky earthquake: Environmental & Engineering Geoscience, v. 14, no. 4, p. 267–280.