Case History

Noise to signal: A microtremor study at liquefaction sites in the New Madrid Seismic Zone

Kelli Hardesty1, Lorraine W. Wolf2, and Paul Bodin3

ABSTRACT

Understanding how sedimentary basins respond to seismic-wave energy generated by large earthquake events is a significant concern for seismic-hazard estimation. This study explores the use of microtremors, or ambient noise, for evaluating strong-motion site effects. The study focuses on the Mississippi Embayment in the New Madrid Seismic Zone, where widespread liquefaction and ground failure occurred during the 1811–1812 earthquake sequence. Spectral analyses of microtremor data at sites representing different environments of deposition (and sedimentary facies), different embayment thicknesses, and varying liquefaction susceptibility show correlations between (1) calculated vulnerability indices and evidence of liquefaction, (2) sediment thickness and fundamental resonant frequency, and (3) subsurface stratigraphic boundaries and observed peaks in horizontal-to-vertical spectral ratios. Results of the study suggest that the microtremor method could be helpful in identifying those areas most vulnerable to ground amplification in intraplate sedimentary basins, where large earthquakes are infrequent but potentially damaging.

INTRODUCTION

The response of soft sediments to seismic-wave energy from large earthquakes represents a long-standing concern to communities located in sedimentary basins, alluvial fans, and similar geologic environments. Historical examples of devastating effects from amplified ground motions in un lithified sediments include such notable events as the 1811–1812 New Madrid earthquakes, the 1985 Mexico City earthquake, the 1995 Kobe earthquake, and the 1999 Chi-Chi earthquake. Many recent studies have focused on understanding how deep-basin sediments respond to seismic energy from large earthquakes. This response is controlled by a variety of factors, including proximity to source, rupture characteristics and directivity, acoustic impedance contrasts, near-surface soil properties, and basin structural configuration. Although the specific mechanism causing wave amplification can vary from site to site, several studies suggest that ambient noise, or weak motions, can be used to identify areas that might amplify earthquake ground motions in advance of earthquake occurrence (e.g., Nakamura, 1989, 1997). In this paper, we investigate the use of microtremors, or ambient noise, using horizontal-to-vertical spectral ratios (HVSRs) to study potential site effects on seismic ground motions in the Mississippi Embayment, a deep sedimentary basin that hosts an active seismic zone. Specifically, we focus on sites located in areas where liquefaction deposits resulting from historic and prehistoric large earthquakes are found. We determine predominant frequencies, relative amplification (among the studied sites), and calculated ground vulnerability derived from the microtremor measurements, and we interpret these results in the context of geotechnical studies, geologic maps, and liquefaction investigations.

BACKGROUND

The Mississippi Embayment forms a southwest-dipping syncline containing un lithified and loosely consolidated alluvial and marine sediments, which are Cretaceous, Tertiary, and Quaternary in age (Figures 1 and 2). Evidence of strong ground motion from large earthquakes in the embayment is ubiquitous. Most prevalent are widespread sand-blow deposits that cover an area of approximately 10,000 km² and straddle the well-defined trends of the New Madrid Seismic Zone (NMSZ). Dating of these deposits indicates that the NMSZ has experienced at least three large earthquake sequences (M ≥ 7.0) with sustained ground motions strong enough to induce soil liquefaction (Figure 1) (Obermeier, 1989; Tuttle et al., 2002). The embayment sediments and underlying Paleozoic basement rock form a high acoustic impedance contrast that can cause seismic ener-
ergy to become trapped in the basin, leading to longer seismic-wave durations and to wave amplification (Bullen and Bolt, 1985). In addition, the synclinal geometry of the embayment strata could focus seismic energy and intensify ground motions. How this thick package of embayment sediments affects seismic-wave energy in the period range of < 10 s is an important consideration for assessing seismic hazard and for predicting the response of engineered structures.

To gain insight into potential effects of embayment sediments on seismic ground motions, we studied HVSRs from recorded microtremors at 15 sites near or in areas of documented soil liquefaction and ground failure. Although the microtremor method is well established, its ability to predict wave amplification and predominant frequency of strong motion has been debated. Previous studies have explored the true source and propagation characteristics of the microtremor (Nakamura, 2000) and the situations in which the method yields predictions consistent with recorded earthquake ground motions (e.g., Ohta et al., 1978; Liu and Heaton, 1984; Field and Jacob, 1993, 1995; Lermo and Chevez-Garcia, 1993; Yamanaka et al., 1993; Bonilla et al., 1997; Nakamura, 1997, 2000; Horike et al., 2001; Bonnefoy-Claudet et al., 2006; Souriau et al., 2007). Although still a topic of debate, a number of microtremor studies have demonstrated that the H/V spectral analysis of data compares favorably with the standard spectral-ratio approach, which calculates a transfer function by comparing weak motions at a reference hard rock to a soft site (Field and Jacob, 1995). The HVSR differs from the standard spectral-ratio method in that a transfer function is computed using only ground motions recorded at a single soft-sediment site, thus eliminating the need for a reference site and making the method particularly attractive for regions that lack bedrock exposures (Nakamura, 1989; Lermo and Chavez-Garcia, 1993):

$$HVSR = \frac{(H_{V} + H_{H})/2}{V_z},$$

where $H_{V}$ and $H_{H}$ are the power spectra of the recorded north and east components of ground motion and $V_z$ is the vertical component. The HVSR method assumes that the vertical component is uninfluenced by low-velocity sediments and that the Rayleigh wave affects the vertical and horizontal components equally (Nakamura, 1989; Woolery and Street, 2002). The resulting spectrum is independent of source and path providing that the sources of noise are azimuthally distributed, a condition that is usually met if recording times are sufficiently long.

Microtremor studies have been used to analyze site characteristics such as resonant frequency, wave amplification, shear-wave velocity, sediment thickness, and liquefaction vulnerability (Lermo and Chavez-Garcia, 1993; Konno and Ohmachi, 1998; Bodin and Horton, 1999; Smith, 2000; and Huang and Tseng, 2002; Woolery et al., 2009). Resonant frequencies appear in the HVSRs as peak amplitudes and are related to sediment thickness and shear-wave velocity. Additional work has demonstrated that HVSRs are repeatable at least in low-frequency ranges (< 10 Hz), in that measurements at different times yield similar spectra (Nakamura, 1989). However, amplitudes measured at different times can be highly variable.

A few specific microtremor studies have been aimed at estimating site response in the Mississippi Embayment. Bodin and Horton (1999) and Smith (2000) observe fundamental periods of approximately 1.5 to 4.6 s at sites distributed across the embayment through Memphis, Tennessee. Using a quarter-wavelength approximation, they correlate these periods with depths to acoustic basement along their transect, where they infer the source as a strong impedance contrast at the interface between sediments and underlying basement rocks. Smith (2000) speculates that a high-frequency peak (2 to 10 Hz) observed in his data corresponds to a prominent loess layer in the Memphis area; however, he makes no explanation of other peaks in the H/V spectra. Woolery and Street (2002) and Woolery et al. (2009) conducted microtremor studies in the northern embayment. The 2009 study in the lower Wabash River Valley compares H/V spectra from ambient noise in the frequency range approximately 2 Hz and above to other methods for estimating site effects, such as $Vs30$ and H/V spectra from earthquake S-waves. Although the results show some similarities in the resulting spectra, overall they observe several inconsistencies among the various methods for this period range (Woolery et al., 2009).

**DATA COLLECTION AND ANALYSIS**

Sites for microtremor data collection were located in the epicentral region of the 1811–1812 earthquakes, where liquefaction deposits are abundant (Figure 1a). Preferred site attributes for selection were (1) presence of liquefaction deposits either at the site or in a nearby area, (2) availability of geotechnical data, such as from seismic cone penetration tests (Romero and Rix, 2001), and (3) nearby (<5 km) well-log information. Specific sites represent common types of sedimentary deposits, which can be grouped into four major divisions: lowlands, braided streams, meandering streams, and transitional between braided and meandering streams (Figure 1b; Saucier, 1994). Letters refer to site abbreviations listed in Table 2.
er, 1994). At least three sites of each deposit type were chosen. Microtremor data were collected using Guralp CMG-4T three-component broadband seismometers, which have a flat instrument response between 0.03 and 100 Hz. At each site, recordings were made at 200 samples per second and for a length of 25 to 30 minutes after the instrument had settled.

Power spectra for each component were used to calculate the HVSR for each site. Data were demeaned and tapered using a maximum Hanning window of 16,348 samples (~ 82 s). The fundamental period $T$ in the HVSR can be related to sediment thickness $H$ and shear-wave velocity $V_S$ by a quarter-wavelength approximation

$$T = \frac{4H}{V_S}.$$  \hspace{1cm} (2)

Fundamental periods observed in the HVSRs were compared to calculated periods using published shear-wave velocities and depths to major (basin-scale) stratigraphic units within the embayment (Figures 2 and 3; Table 1). Depths corresponding to stratigraphic

![Generalized stratigraphic column and cross section](image1.png)

Figure 2. Generalized stratigraphic column and cross section (see Figure 1) for the Mississippi Embayment. For this study, units are grouped into four major geologic age divisions (Cretaceous, Eocene, Paleocene, Quaternary) representing major, basin-scale lithologic boundaries and possibly significant acoustic impedance contrasts.

![Predominant periods derived from HVSRs compared with basin thickness](image2.png)

Figure 3. Predominant periods derived from HVSRs compared with basin thickness for each of the sites used in this study. Thicknesses for each site are from well logs and seismic studies (see Table 1 for data sources). Resonant periods correspondingly increase with increasing sediment thickness and yield an average velocity of 800 m/s.
Table 1. Parameters and sources of stratigraphic units used in this study.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Thickness (m)</th>
<th>Cumulative Thickness (m)</th>
<th>Source (thickness data)</th>
<th>Source (velocity data)</th>
</tr>
</thead>
</table>

Table 2. Observed periods (s) seen in the HVSR and their correlation to stratigraphic boundaries (base of the geologic unit). See Figure 5 for comparison with predicted periods using a quarter-wavelength calculation. A period range not observed is indicated by (—). Site locations shown in Figure 1.

<table>
<thead>
<tr>
<th>Site</th>
<th>Quaternary</th>
<th>Eocene</th>
<th>Paleocene</th>
<th>Cretaceous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shirley Bay (SB)</td>
<td>0.43</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Lake Ashbaugh (LA)</td>
<td>0.31</td>
<td>—</td>
<td>—</td>
<td>0.79</td>
</tr>
<tr>
<td>Black River (BR)</td>
<td>0.55</td>
<td>—</td>
<td>—</td>
<td>0.6</td>
</tr>
<tr>
<td>Payneway (P)</td>
<td>0.58</td>
<td>2.60</td>
<td>—</td>
<td>3.9</td>
</tr>
<tr>
<td>Lester (L)</td>
<td>—</td>
<td>2.85</td>
<td>—</td>
<td>3.4</td>
</tr>
<tr>
<td>Lake City (LC)</td>
<td>0.55</td>
<td>2.20</td>
<td>—</td>
<td>3.4</td>
</tr>
<tr>
<td>Marked Tree (MT)</td>
<td>0.50</td>
<td>—</td>
<td>—</td>
<td>4.1</td>
</tr>
<tr>
<td>Big Lake (BL)</td>
<td>0.74</td>
<td>2.70</td>
<td>—</td>
<td>3.8</td>
</tr>
<tr>
<td>Hornersville (H)</td>
<td>—</td>
<td>2.50</td>
<td>3.00</td>
<td>3.4</td>
</tr>
<tr>
<td>Gilbert (G)</td>
<td>0.62</td>
<td>2.30</td>
<td>3.15</td>
<td>3.7</td>
</tr>
<tr>
<td>RP Haynes (RP)</td>
<td>—</td>
<td>—</td>
<td>3.55</td>
<td>4.3</td>
</tr>
<tr>
<td>Archway (AR)</td>
<td>0.49</td>
<td>3.00</td>
<td>3.60</td>
<td>4.5</td>
</tr>
<tr>
<td>Chickasaw (CH)</td>
<td>0.38</td>
<td>2.80</td>
<td>3.25</td>
<td>4.1</td>
</tr>
<tr>
<td>Bogota (BO)</td>
<td>0.45</td>
<td>3.10</td>
<td>—</td>
<td>3.9</td>
</tr>
<tr>
<td>Reelfoot (RF)</td>
<td>0.40</td>
<td>—</td>
<td>—</td>
<td>3.7</td>
</tr>
</tbody>
</table>

units at each site were derived from a combination of nearby well logs and geologic maps.

RESULTS

Observed fundamental periods versus sediment thickness (basement depth) for all sites are shown in Figure 3 and Table 2 (base of Cretaceous). These range from about 0.5 s at sites near the embayment margin to about 4.5 s at sites in the thickest parts of the basin. Figure 4 illustrates the relation of fundamental resonant period to embayment thickness using four sites selected from the data set. These four sites were chosen because they represent a range of depths to the basement interface (Figure 4b). Figure 4a shows observed values for the peak periods compared with those predicted using embayment thicknesses derived from the sources listed in Table 1 and an average shear-wave velocity of 800 m/s for sedimentary strata within the basin (above basement rocks) (Figure 3). Differences between predicted and observed values are less than 0.25 s for these sites. Uncertainties for the observed peak periods were estimated by taking the width at two-thirds the maximum peak height. Figure 4 shows that the fundamental resonant periods shift to longer periods with increasing embayment thickness, suggesting that they are most likely related to the impedance contrast at the basement-sediment interface.

In addition to spectral peaks associated with the basement interface, higher frequency peaks in the HVSRs also are observed (e.g., Figure 4 and Table 2). Figure 5 compares the observed spectral peaks for each site with peaks predicted using published depths to major stratigraphic boundaries within the embayment (Figure 2) and average shear-wave velocities to the boundaries. The intermediate boundaries used in the forward calculation represent the base of the stratigraphic unit and are labeled, from bottom to top, as Paleocene (Figure 5b), Eocene (Figure 5c), and Quaternary (Figure 5d). Thicknesses and velocities used in calculating the predicted values were taken from sources listed in Table 1 and were based on data from well logs, seismic refraction and reflection surveys, geotechnical investigations, and geologic mapping. Good agreement between predicted and observed frequencies for the intermediate-depth boundaries (Figures 5b and c) suggests these peaks could be associated with major lithologic boundaries at the base of Paleocene and Eocene strata (Figure 2). However, there is less agreement associated with the base of Quaternary-age sediments (Figure 5d).

INTERPRETATION OF HVSR

In microtremor studies conducted farther south in the embayment, Bodin and Horton (1999) and Smith (2000) observe fundamental periods from about 1.5 to 4.6 s, similar to those observed in this study. They also correlate these periods with a strong impedance contrast at the interface between sediments and underlying basement rocks. Smith (2000) speculates that a high-frequency peak (2 to 10 Hz) observed in his data corresponds to a prominent loess layer in the Memphis area. He does not, however, speculate on the relation of intermediate-period peaks to deeper layers within the basin, despite their appearance in the HVSRs. Based on our observations, we suggest that peaks in the range of 1.8 to 3.1 s (Figure 5c) correspond to the top of the Porter’s Creek Clay, a major, regionally extensive confining unit of Paleocene age (Figure 2). Peaks in the range of 2.8 s to 3.6 s (Figure 5b) appear to correspond to carbonate sand in the Cretaceous strata. We speculate that data from sites not displaying intermediate peaks at the predicted periods indicate the presence of a gradational change in velocity (and thus weak imped-
ance contrast) at the respective interfaces, or structural complexity (e.g., basin curvature). Although there is more scatter between observed and predicted periods associated with the Quaternary boundary in Figure 5d, the maximum deviation is about the same as in the other boundaries (~0.2 s). Like Smith (2000), we identified a spectral peak around 1.5 s in the data (see Figure 4); although this peak appears prominently at several sites, we could not correlate it with a stratigraphic boundary and its source is not known. Higher-frequency peaks (>2 Hz) are observed in all records but these peaks appear to be unstable. Variability of peaks in the high-frequency range (>2 Hz) was also noted in the microtremor study of Woolery et al. (2009).

Nakamura (1997, 2000), Konno and Ohmachi (1998), and Huang and Tseng (2002) propose the use of a vulnerability index $K_g$ to identify sites most susceptible to strong ground shaking. Index $K_g$ is derived from peak periods in the spectra $T$ and their associated amplitudes $A_p$, where

$$K_g = T \times A_p^2.$$ (3)

Nakamura (2000) derives the $K_g$ index with the underlying assumption that accelerations experienced in basement rocks in a given area will not vary significantly and thus the effective shear strain recorded at the ground surface can be used as a relative measurement of a site’s vulnerability with respect to other sites in the same area. In their microtremor study after the 1999 Chi-Chi, Taiwan earthquake, Huang and Tseng (2002) use this technique to map vulnerability in the Yuan-Lin area of the alluvial fan. They note generally higher $K_g$ values for sites that experienced severe liquefaction.

Figure 6 shows resonant periods, amplifications, and calculated vulnerability ($K_g$) indices for the 15 study sites. Sites are ordered from west to east, and follow shallow-to-deep basement depths. The type of deposit at each site location is indicated by symbol type on the data plots. Fundamental periods are progressively longer for central parts of the embayment and amplifications are generally higher.

![Figure 4](image-url)

Figure 4. Results from four microtremor sites selected to illustrate the methodology used in this study. (a) Table showing predicted and observed resonant periods for the four site locations. Predicted periods $T$ are calculated by $T = 4H/V_S$ where $H$ = embayment thickness and $V_S$ = shear-wave velocity. Errors in determining spectral peaks are estimated by taking the width of peak at two-thirds the peak height as shown in (c). (b) Cross section through study area showing major stratigraphic boundaries with sites indicated. (c) $HV$ power spectral ratios of four selected sites. Letter abbreviations as in Table 2. Note that peak shifts towards longer periods as embayment thickness increases.
along the basin margins and in central parts of the basin. We caution, however, that the amplifications should be considered only in a relative sense, because we have conducted no comparison with recorded earthquake ground motions. The highest vulnerability indices are associated with sites located in the meandering stream deposits of the embayment east of the Mississippi river. In their study of site effects in Lourdes, France, Souriau et al. (2007) note good agreement between HVSRs and sediment type. Based on our limited data set, we cannot confidently endorse the reliability of using vulnerability indices to map site amplification or liquefaction susceptibility; however, we note that sites in our study located in areas that have the greatest percentage of sand-blow deposits at the surface (Obermeier, 1989; Tuttle et al., 2002) also yielded relatively high $K_g$ values with respect to sites in areas where liquefaction deposits are less abundant. Several of the sites that have high $K_g$ values also showed relatively high liquefaction susceptibility in near-surface sediments, as determined by geotechnical penetration tests (Schneider and Mayne, 1998; Romero and Rix, 2001). Although liquefaction is a near-surface phenomenon, characteristics of deeper basin strata (impedance contrasts, basin geometry, etc.) influence seismic-wave propagation, possibly making some sites more prone to strong ground shaking. Taken together, results suggest that high $K_g$ values in the presence of susceptible soils (as determined by penetration tests) might be used to help identify sites most vulnerable to strong shaking.

Figure 5. Observed (gray) versus calculated (black) periods and their relation to major stratigraphic boundaries within embayment sediments (see Table 2). Calculated periods are based on depths of stratigraphic boundaries at each site derived from published data (see Table 1). Average shear-wave velocity ($V_S$) to the boundary is indicated in each panel. Good agreement between spectral peaks observed in the HVSRs and those calculated for the Eocene and Paleocene boundaries suggests that lithologic changes at these depths could produce impedance contrasts that amplify energy at the frequencies indicated. Scatter between observed and predicted peaks from the base of Quaternary sediments suggests that the HVSRs might not be reliable at higher frequencies, although the maximum deviation from the predicted values is comparable to that observed with other boundaries.
HVSRS technique, coupled with geotechnical tests of near-surface sediments, could be a useful tool for identifying sites most susceptible to strong ground shaking from incoming earthquake energy. However, we caution that this observation is limited to a small number of sites and additional work is required.

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REFERENCES


———, 1995, A comparison and test of various site-response estimation techniques, including three that are not reference-site dependent: Bulletin of the Seismological Society of America, 85, 1127–1143.


———, 1995, Seismic vulnerability indices for ground and structures using Hv from spectral ratios with only one station: Bulletin of the Seismological Society of America, 78, 710–730.


Romero, S., and G. Rix, 2001, Ground motion amplification of soils in the up...

CONCLUSIONS

Like previous studies, our study suggests that the HVSRS method is a potentially useful tool for determining site effects in sedimentary basins, particularly for areas in which large earthquakes are known to have occurred but are infrequent. Results of this study suggest that several dominant peaks observed in the frequency spectrum can be correlated to major stratigraphic boundaries in the Mississippi Embayment, although we could determine little correlation with stratigraphic interfaces at higher frequencies. Although we lack empirical knowledge of the impedance contrast at deep stratigraphic interfaces at our specific site locations, well-log information from nearby sites suggests these interfaces represent significant regional lithologic (and likely velocity) changes and are the most probable source of spectral peaks. The correlation of abundant liquefaction deposits at sites that have the highest vulnerability or K_s indices suggests that...
per Mississippi Embayment: Mid-America Earthquake Center, Technical Report No. GIT-CEE/GEO-01-1.