A Study of Horizontal-to-Vertical Component Spectral Ratio in the New Madrid Seismic Zone

by Arash Zandieh and Shahram Pezeshk

Abstract The horizontal-to-vertical component (H/V) spectral ratio of the small and moderate earthquake ground motions for the shear-wave window was used as an estimation of the site response in the New Madrid seismic zone (NMSZ). The database used in this study consisted of 500 broadband seismograms from 63 events of magnitude $M_w$ 2.5 to 5.2, recorded on 11 stations operated by the University of Memphis Center for Earthquake Research and Information (CERI) at the University of Memphis. All the broadband stations were located within the Mississippi embayment. Soil deposits overlying the rock basement of the embayment strongly affected the amplitudes of the ground motions. The horizontal-to-vertical component ratios were evaluated for the frequency range of 0.2 to 20 Hz. The observed average H/V ratios suggested site amplification between 2 and 4 in the low-frequency range ($f \leq 5$ Hz) for stations located on the lower shear-wave velocity deposits (lowlands). The higher shear-wave velocity deposits (uplands) indicated low-frequency amplification between 1.5 and 3 Hz. The observed average H/V ratios were also compared with the soil amplifications in the upper Mississippi embayment developed by Romero and Rix (2005) from the 1D (equivalent linear) method for generic regional profiles. The H/V ratios were also compared with the theoretical quarter-wavelength approximation. These comparisons suggested that the H/V ratios could be a first estimate of the site amplifications.

Finally, the variability of the H/V ratios with distance was examined and no discernible trends were found; therefore, the path effect model developed by Zandieh and Pezeshk (2010) for the vertical ground motions in NMSZ using the database of this study was also applicable for the horizontal ground motions.

Introduction

The amplification effect of local soil sediments on earthquake ground motion had been well established in earthquake engineering and engineering seismology. Site effects played an important role for site-specific ground-motion predictions and seismic hazard analysis. One of the standard empirical methods for evaluating site effects was to utilize earthquake recordings. In this method, site effects were evaluated as the spectral ratios of the recorded earthquake ground motions at free-field stations located on soil with those recorded on a reference rock station (Borchert, 1970). This method was optimized when both the reference station and free-field (soil) stations recorded the same events. Furthermore, the location of the reference station with respect to others should have been such that the path effect did not affect the incidence ground motion. Other factors such as basin shape (i.e., Mississippi embayment, etc.) could focus or defocus the ray paths within a basin, but not at the rock site outside the basin. Lermo and Chávez-García (1993) presented an alternative empirical method based on Nakamura’s (1989) technique to estimate the soil transfer function without a reference station. Nakamura (1989) used the horizontal-to-vertical component (H/V) spectral ratio to analyze Rayleigh waves and dynamic properties of the subsurface using microtremor recordings; however, Lermo and Chávez-García (1993) showed that the Nakamura technique could be applied to the shear-wave part of earthquake records to evaluate the site effects. They found an agreement between the H/V ratios and the standard spectral ratio at their sites and showed that the H/V ratios were a robust estimate of the first resonant mode frequency and amplitude of the soil deposits. Bour et al. (1998) used Nakamura’s technique on microtremor recordings to establish the seismic microzonation in terms of a predominant frequency map of a plain near the Rhone delta (south of France). Bour et al. (1998) found agreement of the fundamental frequencies between the H/V ratios and the numerical transfer functions of soil columns in the regions. Atkinson and Cassidy (2000) studied the amplification effects of deep
seds of the Fraser River delta, British Columbia, using earthquake ground motions. They found that weak motions were amplified between three and six times in the Fraser River delta over a broad frequency range (i.e., 0.2 to 4 Hz) with the high-frequency motions more attenuated. They compared the estimated amplifications with the observed H/V ratios and concluded that the H/V ratio appeared to be a reasonable first approximation of site effects (Atkinson and Cassidy, 2000). They found good agreement between H/V ratios and theoretical amplifications although H/V ratios underestimated, consequently the amplification at low-frequencies. They also showed that the H/V ratio for rock sites in western British Columbia matched the amplification calculated using the quarter-wavelength approximation based on the regional shear-wave velocity profile. Siddiqqi and Atkinson (2002) used the H/V ratio to determine the amplification of rock sites across Canada. Their database consisted of 424 earthquakes, recorded on rock sites by the Canadian National Seismograph Network, with a magnitude 2 or larger. The average H/V ratios were consistent with the expected amplification due to shear-wave velocity gradient for rock sites. The average H/V ratios increased from unity for low frequencies to a factor of 1.2 to 1.6 at high frequencies (10 Hz). They also found a correlation for H/V ratios with local geological conditions (Siddiqqi and Atkinson, 2002). Woolery et al. (2009) studied the suitability of the evaluated horizontal-to-vertical ratio of ambient noise and also the time-averaged shear-wave velocity of the upper 30 m of soils and rock at a site ($V_{S30}$) from the shallow seismic refraction/reflection profiles for estimating site effects in the lower Wabash River valley area of southern Indiana and Illinois. They also used the H/V ratios of the shear wave for the southwestern Indiana earthquake of 18 June 2002 for estimating site effects. These methods were compared with linear 1D site amplification approximations. There was only a weak correlation between the linear 1D amplification curves and the site effects predicted by the two horizontal-to-vertical ratios or the $V_{S30}$ classification of the site. Woolery et al. (2009) found that earthquake H/V ratios along with the site-specific 1D modeling did a better job of predicting observed ground motions than ambient noise H/V ratios. However, they emphasized the need for additional observation from sufficient events to evaluate the effectiveness of the technique.

We had two objectives for this study. The first objective was to evaluate the H/V ratios as an estimation of the sediment amplification in the New Madrid seismic zone (NMSZ). Our database consisted of 500 broadband seismograms from 63 events recorded by the University of Memphis Center for Earthquake Research and Information (CERI) with magnitudes between $M_w$ 2.5 and 5.2. Zandieh and Pezeshk (2010) used the same database to study the path effect for vertical-component ground motions in the NMSZ.

The second objective was to examine the variability of H/V ratios with distance for small and moderate earthquakes in the NMSZ. Zandieh and Pezeshk (2010) studied the regional path effect in the NMSZ using the vertical component of the broadband earthquake dataset. They determined the path effect as the geometrical spreading and quality factor functions for the NMSZ; therefore, by evaluating the H/V ratio variability with distance, we demonstrated whether the path effect derived in Zandieh and Pezeshk (2010) was applicable for the horizontal-component ground motions as well. Atkinson (2004) developed the attenuation model for the vertical component, due to the paucity of the horizontal data, and applied it to the horizontal-component database. After she examined the residuals, Atkinson found no trends with distance; therefore, an independent model for horizontal component was not necessary. The H/V ratio, as an approximation of the site amplification, was then applied to the vertical-component model to predict the horizontal component (Atkinson, 2004).

**Database**

Our project used three-component broadband seismograms from 11 CERI seismic network stations. These stations and their identifications are listed in Table 1. All the broadband stations were located in the Mississippi embayment with different site conditions based on their different depths to basin and potential regional differences in soil properties.

**Table 1**

<table>
<thead>
<tr>
<th>Station Name</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation (m)</th>
<th>Sensor</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLAT</td>
<td>36.26937</td>
<td>-89.28756</td>
<td>120.0</td>
<td>CMG40T</td>
<td>Glass, TN</td>
</tr>
<tr>
<td>GNAR</td>
<td>35.9652</td>
<td>-90.0178</td>
<td>71.0</td>
<td>CMG40T</td>
<td>Goshell, AR</td>
</tr>
<tr>
<td>HALT</td>
<td>35.91060</td>
<td>-89.33953</td>
<td>85.0</td>
<td>CMG40T</td>
<td>Halls, TN</td>
</tr>
<tr>
<td>HBAR</td>
<td>35.5550</td>
<td>-90.6572</td>
<td>74.0</td>
<td>CMG40T</td>
<td>Harrisburg, AR</td>
</tr>
<tr>
<td>HICK</td>
<td>36.5409</td>
<td>-89.2288</td>
<td>141.0</td>
<td>CMG40T</td>
<td>Hickman, KY</td>
</tr>
<tr>
<td>HENM</td>
<td>36.7160</td>
<td>-89.4717</td>
<td>88.0</td>
<td>CMG40T</td>
<td>Henderson Mound, MO</td>
</tr>
<tr>
<td>LNXT</td>
<td>36.10138</td>
<td>-89.49127</td>
<td>144.0</td>
<td>CMG40T</td>
<td>Lenox, TN</td>
</tr>
<tr>
<td>LPAR</td>
<td>35.6019</td>
<td>-90.3002</td>
<td>66.5</td>
<td>CMG40T</td>
<td>Lepanto, AR</td>
</tr>
<tr>
<td>PARM</td>
<td>36.6635</td>
<td>-89.7522</td>
<td>85.0</td>
<td>CMG40T</td>
<td>Stahl Farm, MO</td>
</tr>
<tr>
<td>PEBM</td>
<td>36.11312</td>
<td>-89.86229</td>
<td>76.0</td>
<td>CMG40T</td>
<td>Penscott Bayou, MO</td>
</tr>
<tr>
<td>PENM</td>
<td>36.4502</td>
<td>-89.6280</td>
<td>85.0</td>
<td>CMG40T</td>
<td>Penman, Portageville, MO</td>
</tr>
</tbody>
</table>
The database consisted of 500 broadband seismograms from 63 events of magnitude $M_w$ 2.5 to 5.2. All the earthquakes occurred between 2000 and 2009. We used the high gain channel with sampling rate of 100 samples per second. The hypocentral distances ranged between 10 and 400 km. A map of CERI’s broadband stations along with the location of earthquakes used in this study is shown in Figure 1.

In this study, the spectral ratios of the horizontal-to-vertical components for the shear-wave window of the waveforms were evaluated. Each waveform contained direct, reflected, and refracted phases of both $S$ and $P$ waves. Atkinson and Mereu (1992) and Atkinson (2004) used the shear window, a part of the signal containing shear-wave phases (i.e., $S$, $S_mS$, $Lg$, $S_n$, etc.). At near distances (i.e., less than 70 to 100 km) the shear window contained the direct shear wave. As distance increased, the direct shear wave was joined by reflections from crustal interfaces and the Moho discontinuity. At regional distances of several hundred km (200 to 1000 km), the shear window included the $S_n$ and $Lg$ phases. For each waveform used in our study, including the two horizontal and the vertical components of each record, the Fourier amplitude of the shear-wave window was evaluated and corrected for the noise. To obtain the Fourier spectrum of the signal while excluding the noise, we used the Welch’s method of power spectral density (PSD) estimation (Welch, 1967). Welch’s method consisted of dividing the time series data into overlapping segments, computing periodogram (squared amplitude of discrete-time Fourier transform) of each windowed segment, and then averaging the PSD estimates. In this study, we used 256 sample segments with 50% overlap. Each segment was windowed using the Hamming window to minimize the spectral leakage between frequencies. For the sampling rate of 100 samples per second, the duration of each segment was 2.5 seconds and 1024 Fourier transform points were used while evaluating the fast Fourier transform (FFT) of the windowed segment; therefore, the frequency bins from FFT were 0.0977 Hz wide.

The recorded waveforms were first corrected for the instrument response using the instrument transfer function. Then the velocity was converted to acceleration and the PSD of acceleration was calculated using the Welch’s method. The obtained power spectra should have been corrected for the noise. The noise window for each waveform was one segment of the record ahead of the shear-wave window arrival. For the case where the noise segment contained the $P$ wave, a segment preceding the $P$ wave was selected as the noise window. In other words, the preevent noise was removed from the signal. The noise window was processed in the same way as the signal and the noise PSD was calculated. The PSD of the noise-corrected acceleration signal was evaluated by subtracting the noise PSD from the signal (i.e., the shear-wave window) PSD. The Fourier amplitude of the noise-corrected acceleration was the square root of the calculated power spectra. The signal-to-noise ratio was evaluated for each record for different frequencies and data were selected for further analysis only at frequencies for which the signal-to-noise ratio exceeded 2.

The Fourier spectrum of ground acceleration for each waveform in the database was obtained using the discussed method for the north–south, east–west, and vertical components and the H/V ratios for east–west and north–south components were evaluated and tabulated for frequencies between 0.2 and 20 Hz.

The New Madrid Seismic Zone Geology

The NMSZ is located in the central United States in the mid-Mississippi River valley. It was the source for the 1811–1812 large ($M_w \geq 7.0$) earthquake sequence. A detailed summary of geological and seismological studies of the NMSZ along with interpretations on historical seismicity can be found in Johnston and Schweig (1996). The Mississippi embayment is a large wedge-shaped synclinal structure that dips south along its primary axis from southern
Illinois to the Gulf of Mexico, and is filled with post-
documented the stratigraphic characteristics for these depos-
its in the upper Mississippi embayment. In general, these
sediments consisted of sand, silt, and clay with thickness
from 477 m at New Madrid, Missouri, to 1 km near
Memphis, Tennessee (Van Arsdale and TenBrink, 2000). The
ground motions in the region were affected by the thickness
and dynamic properties of these deep soil deposits, as well as
the basin effects that trapped the seismic energy within the
embayment. A contour map for thickness of the sediments on
top of the Paleozoic basement in the upper Mississippi
embayment from Van Arsdale and TenBrink (2000) is shown
in Figure 2.

Toro et al. (1992) classified the embayment into two
regions based on the age of near-surface geologic deposits.
These two regions consisted of the recent Holocene-age
alluvial deposits in floodplains, called lowlands, and the old-
er Pleistocene-age terrace deposits, called uplands. Romero
and Rix (2005) studied the effect of the deep soil deposits in
the upper Mississippi embayment. They developed generic
shear-wave velocity profiles for the lowlands and uplands
deposits up to 70 meters by aggregating the characteristic
profiles (profiles represented the typical profile for a particu-
lar area based on compiled profiles with an uncertainty
defined from the site-specific analysis) obtained for the
Memphis Metropolitan Area (MMA) and measured profiles
outside the MMA based on their geologic location within the
Mississippi embayment. The lowlands deposits had lower
shear-wave velocities in the upper 70 meters compared with
the uplands deposits. Romero and Rix (2005) then used the
shear-wave velocity of geologic deposits that had previously
been estimated to the Paleozoic basement for several sites in
the upper Mississippi embayment and generated a $V_s$ profile
for deep soils extending from 70 meters to the maximum
depth of the upper Mississippi embayment at an approximate
depth of 1000 meters. This deep soil profile was combined
with both the lowlands and uplands profiles to create a $V_s$
profile for the entire soil column. Finally, they used the
Catchings (1999) crustal model developed for Memphis,
constrained by both seismic refraction and gravity modeling,
as the crustal velocity structure for geologic deposits below
1000 meters and developed final generic profiles. The effect
of varying embayment depths to determine the site effects
was considered by truncating the embayment model at
depths of 1000, 600, and 100 meters and extending the
crustal model to maintain a constant crustal thickness.

The physiographic features of lowlands and uplands
deposits are shown in Figure 3. Based on the Romero and
Rix (2005) classification of the embayment, stations GLAT,
HALT, HICK, and LNXT lie on the lowlands deposits and
stations GNAR, HBAR, HENM, LPAR, PARM, PENM, and
PEBM lie on the uplands deposits.

Results

The calculated H/V ratios for each station at each direc-
tion showed event-to-event variability. We used the mean H/
V ratio of all events as the indicative H/V ratios for each
station. The event-to-event variability was described as the
standard deviation of the H/V ratios and 90% confidence in-
terval for the mean. For example, the H/V ratios, their mean,
standard deviation, and 90% confidence intervals of the mean for stations HICK and LPAR are shown in Figure 4 for the north–south direction. Another important consideration was the variability of the H/V ratios for each of the horizontal components. The results showed consistency between the mean of H/V ratios for each direction. As an example, the mean H/V ratios for each of the east–west and north–south directions were compared for stations GLAT and GNAR in Figure 5. The mean H/V ratios for both directions were similar; therefore, for the remaining results we only showed the east–west direction for brevity. The mean and the standard deviation for the H/V ratios from all 11 broadband stations are shown in Figure 6a. The H/V ratios for stations lying on the lowlands and uplands deposits were separated in Figure 6b. All the stations located on lowlands showed amplifications between 2 and 4 in the low-frequency range (i.e., $f \leq 5$ Hz). For higher frequencies, the H/V ratio decreased with the exception of some individual peaks. Among all the stations on lowlands, the amplifications at station PEBM had an anomalous shape with a peculiar large amplification factor of about 5 at the frequency near 5.3 Hz. This behavior was not observed in the station GNAR, which was the closest station to PEBM (40 km spaced out) with the same depth to Paleozoic based on the van Arsdale and Ten-Brink (2000) map shown in Figure 2. This was probably caused by a local geologic structure. This was also a limitation with all the ground-motion response predictions and observations. Woolery et al. (2009) found in their study on Wabash River valley that deeper geologic rock structure,
as well as lateral geologic variation on the scale of a few 10s to 100s of meters, could have significant effects on the ground-motion response predictions and observations. Although their study was outside the embayment where 3D effects were less problematic with observational data, it was still germane globally. Stations lying on uplands amplified the weak motions by a factor of 1.5 to 3 for the frequency range of $f \leq 5$ Hz with the exception of station LNXT, which had a peak $H/V$ ratio of about 3.8 near 3 Hz. Station LNXT was located on the lowlands–uplands boundary and had a similar site amplification as lowlands observations. It should be noted that the reported

Figure 6. Observed mean $H/V$ ratios for all the stations: (a) The mean $H/V$ ratios for each of the 11 stations. The error bars show the standard deviation. (b) The mean $H/V$ ratios for stations classified by their location on uplands or lowlands profiles. The color version of this figure is available only in the electronic edition. (Continued)
amplification factors were based on mean H/V ratios and individual H/V ratios were as large as a factor of 7 in some cases; therefore, the standard deviation in H/V ratios should have been considered for the estimated amplifications. As a general observation, in lowlands region, the stations located on thinner deposits (see Fig. 2) showed higher amplifications at a frequency range of between 5 and 15 Hz compared with stations that had higher depth to the Paleozoic basement. The site amplifications presented in this study were compared with those developed by Romero and Rix (2005) for the upper Mississippi embayment. The site amplifications in Romero and Rix (2005) were evaluated for the generic shear-wave velocity profiles that were developed for the central United States and Mississippi embayment. They used the stochastic method to simulate the rock motions at the base of soil columns; a 1D equivalent-linear site response analysis was employed to calculate the site amplifications. The site response in the scheme of Fourier amplification was the ratio of Fourier amplitudes of the estimated ground motion at the ground surface to that of the rock ground motion. The detailed geotechnical and seismological factors used to evaluate the site amplification are not discussed here. For further information on the geotechnical and seismological factors and their effects on the calculated site factors, readers are referred to Romero and Rix (2005).

In the Romero and Rix (2005) study, soil parameters including the shear-wave velocity profiles and dynamic material properties were randomized to account for uncertainty; 30 simulations were performed for each scenario earthquakes. The amplifications reported in their study were the median of the simulations for a reference earthquake scenario with a moment magnitude of 6.5 and an epicentral distance of 50 km on the NEHRP site class A ($V_s = 2040$ m/s) hard rock base. The median PGA for this scenario earthquake was 0.076 (g) for the rock motion. The two profiles considered were the uplands and lowlands profiles with three embayment depths for each of these soil profiles: (1) 100 meters, (2) 600 meters, and (3) 1000 meters (Romero and Rix, 2005). It should be noted that the ground-motion intensities of the events in the database were low enough to prevent any nonlinear soil behavior; therefore, we used linear site amplifications reported by Romero and Rix (2005) for a consistent comparison. In Figure 7, the site amplifications for their uplands soil profile with the depths of 100, 600, and 1000 meters are compared with the H/V ratios for stations GLAT, HALT, HICK, and LNXT. Also, the same comparison was made for the lowlands soil profile and the H/V ratios for stations GNAR, HENM, PENM, PARM, and LPAR. In Figure 7, the Romero and Rix (2005) amplifications are given only for soil column depths of 100, 600, and 1000 meters; the basin effect was not included in the site response analysis while the stations were located on different thicknesses of soil (Fig. 2) within the embayment. This fact made it difficult to carry out a fair comparison. Based on the fundamental differences between the two methods, a quantitative comparison was not appropriate. Romero and Rix (2005) predicted lower amplification for frequencies greater than 1.5 Hz in lowlands and higher amplification for frequencies greater than 3 Hz in uplands. However, the H/V ratios were relatively consistent with the Romero and Rix (2005) amplifications for low frequencies of $f \leq 2$ Hz for both lowlands and highlands. It seemed that the Romero and Rix (2005) amplifications dropped off more rapidly than H/V ratios for high frequencies.

Our H/V ratios were also compared with the theoretical amplification estimated by the quarter-wavelength method (Joyner et al., 1981). The linear characteristic of the method was compatible with the weak ground motions used in this study. The frequency-dependent amplification factors calculated using quarter-wavelength approximation were smooth; moreover, the method did not account for resonance effects. In this study, we used the result of the quarter-wavelength approximation applied to the upper Mississippi embayment by Romero and Rix (2005). They used the quarter-wavelength method on the uplands and lowlands generic profiles and used the kappa value of 0.048 s for deposits in the embayment reported by Herrmann and Akinsci (2000). The parameter kappa ($\kappa$) defined a low-pass filter.
of the form $\exp(-\pi \kappa f)$ that attenuated high-frequency energy (Anderson and Hough, 1984). Our H/V ratios were compared with the site amplifications calculated using the quarter-wavelength method by Romero and Rix (2005) for the uplands and lowlands profiles (Fig. 8). The quarter-wavelength approximation for the uplands profile was compared with the H/V ratios for stations GLAT, HALT, HICK, and LNXT. Also, the same comparison was made for the lowlands soil profile and the H/V ratios for stations GNAR, HENM, PENM, PARM, and LPAR. The H/V ratios correlated with the theoretical quarter-wavelength estimates for the uplands profile for frequencies less than 10 Hz. The H/V ratios on average showed higher estimations than the quarter-wavelength method for uplands. The lowlands profile also correlated with the quarter-wavelength method, except in the frequency range between 2 and 8 Hz where the H/V ratios had higher values than the quarter-wavelength approximations. Larger peaks observed at specific frequencies were likely the result of resonant effects that were not accounted for in the quarter-wavelength method (Atkinson and Cassidy, 2000).

The agreement between H/V ratios and quarter-wavelength estimates suggested that the H/V ratios could be a first approximation of the site effects. Obviously, the two methods were not correlated in all bandwidths based on the fundamental differences between them. The smooth prediction of the quarter-wavelength method was because it did not account for the resonant effects in the soil column (Atkinson and Cassidy, 2000), while multiple peaks were observed in the H/V ratios in specific frequencies.

Another aspect of this study was to examine the variability of H/V ratios with distance. Zandieh and Pezeshk (2010) analyzed the vertical-component ground motions using the same database as in this study and determined that the path effect considering the geometrical spreading and quality factor functions for the NMSZ. By characterizing...
the variability of H/V ratios with distance, one could determine if the path effect derived in Zandieh and Pezeshk (2010) for the vertical-component was applicable for the horizontal-component ground motions as well. At each frequency, we plotted the individual H/V ratios for all stations against distance and examined the trend by fitting a straight line. The frequency steps for the Fourier amplitudes were approximately 0.0977 Hz (∼0.1 Hz) based on our signal processing. We also evaluated the standard error for the slope of the fitted line (Montgomery and Runger, 2002). As a typical example, the plots of H/V ratios versus distance at frequencies of 1 and 5 Hz are shown in Figure 9, along with the fitted straight line to the data points and the standard error of the slope. The slope was 0.0009 and its standard error was 0.0005 for 1 Hz. At 5 Hz the slope was 0.0006 and its standard error was 0.0008. For all the frequencies, the slope of the fitted line was close to zero and its standard error was between 0.0005 and 0.0009. We evaluated the confidence intervals of the slope using the t-distribution (Montgomery and Runger, 2002). Considering a slope of 0.0009 with the standard error of 0.0009, the 95% confidence interval on the slope of the regression line was [−0.0009, 0.0027]. We interpreted that there was no significant trend apparent in H/V ratios versus distance. This led us to conclude that the path model developed for the vertical component ground motion for the NMSZ region in Zandieh and Pezeshk (2010) could be used to describe the path effect for horizontal components as well. The path term developed in Zandieh and Pezeshk (2010) consisted of a hinged-trilinear geometrical spreading function and a frequency-dependent quality factor function. Their analysis of the geometrical spreading indicated that at distances less than 70 km the spectral amplitudes decayed as $R^{-1}$, between 70 and 140 km the spectral amplitudes increased with distance and the geometrical spreading was defined as $R^{+0.25}$. Beyond 140 km, the attenuation was described by $R^{-0.5}$. The quality factor function was expressed as $Q = 614 f^{0.32}$ for frequencies greater than 1 Hz (Zandieh and Pezeshk, 2010).

Conclusions

Lermo and Chávez-García (1993) showed that the Nakamura (1989) H/V ratio technique could be applied to the shear-wave part of the recorded ground motions, and the H/V ratios provided a reasonable estimate of the first resonant mode frequency and amplitude of the soil deposits. We applied the H/V ratios of the shear-wave window for the recorded ground motions to sites in the NMSZ for site effect evaluation. The database consisted of 500 seismograms from 63 events between magnitude $M_w$ 2.5 and 5.2 that were recorded by 11 CERI broadband stations. The calculated H/V ratios at each station showed considerable event-to-event variability; therefore, the mean H/V ratios for all events were used as an indicator of the site amplification for the sites. Stations located on lowlands deposits amplified the weak motions by factors of 2 to 4 at low-frequencies range, and stations located on uplands deposits showed amplification factors between 1.5 and 3 at low frequencies ($f \leq 5$ Hz). The mean H/V ratios were compared with the soil amplifications derived by Romero and Rix (2005) for lowlands and uplands generic profiles using the 1D equivalent-linear. The H/V ratios were relatively consistent with the Romero and Rix (2005) amplifications for the low frequencies of $f \leq 2$ Hz, while for high frequencies the Romero and Rix (2005) amplifications dropped off more rapidly than H/V ratios. Romero and Rix (2005) predicted a lower amplification for frequencies greater than 1.5 Hz in lowlands and a higher amplification for frequencies greater than 3 Hz in uplands.

The observed H/V ratios were also compared with the quarter-wavelength method. The H/V ratios were in good agreement with the theoretical quarter-wavelength estimates for the uplands and lowlands profiles within certain bandwidths (less than 10 Hz for uplands and outside the range between 2 and 8 Hz for lowlands), suggesting that the H/V ratios could be a first approximation of the site effects. The smooth prediction of the quarter-wavelength method

\[ y = 0.0009x + 2.2353 \]

\[ y = 0.0006x + 2.0909 \]

Figure 9. Observed H/V ratios versus distance for frequencies of (a) 1 Hz and (b) 5 Hz (circles). The solid lines are the fitted straight lines to data points. The equation of the fitted lines along with the standard error of the slope, stderr (slope), are also shown.
was because it did not account for the resonant effects in the soil column (Atkinson and Cassidy, 2000) while multiple peaks were observed in the H/V ratios in specific frequencies.

The variability of the H/V ratios with distance was also examined and no discernible trends were found; therefore, the path effect model developed by Zandieh and Pezeshk (2010) for the vertical ground motions in NMSZ was applicable for the horizontal ground motions as well. The path term included a hinged-trilinear geometrical spreading function and a frequency-dependent quality factor function.

Data and Resources

Seismograms used in this study were collected as part of the Advanced National Seismic System (ANSS) of the central and eastern United States. Data can be obtained from the ANSS from http://earthquake.usgs.gov/monitoring/anss/regions/mid/ (last accessed April 2010).

Acknowledgments

We wish to thank many people who contributed data, information, or criticisms. In particular, we wish to thank Mitch Withers for providing broadband seismograms and Heather DeShon and Christy Chiu for helping in data processing. We thank Gail Atkinson for her insightful and constructive guidance. We also thank anonymous reviewers for their thorough comments and suggestions, which greatly helped improve the article.

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Manuscript received 5 May 2010