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Site amplification within the Mississippi embayment of the central United States: Investigation of possible differences among various phases of seismic waves and presence of basin waves

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ABSTRACT

The impact of unconsolidated sedimentary basins on ground motion amplification is of particular interest for earthquake engineers and seismologists. The Mississippi embayment (ME) of the New Madrid seismic zone, located in the central United States, is covered with a thick layer of unconsolidated soil deposits. Thus, the estimation of site response in this region is vital to simulate site-specific ground motions and to conduct site-specific probabilistic seismic hazard analysis. We evaluated site amplification at 11 stations within the ME, employing the horizontal-to-vertical spectral ratio (HVSR) technique.

Regarding the results obtained from this study, weak ground motions recorded by stations on the unconsolidated ME sediments are amplified 3–7 times for frequencies less than 5 Hz compared to stations located on bedrock. The fundamental resonant frequencies vary from 0.2 to 0.4 Hz within the ME. We investigated differences between the HVSRs obtained from *P*-waves, *S*-waves, coda, and pre-event noise. All fundamental frequencies obtained from different seismic phases are in good agreement with a less than 10% difference. The fundamental frequencies of the *P*-wave and *S*-wave are relatively higher due to higher velocity of the *P*-wave and *S*-wave compared to other phases since the velocity of seismic waves and fundamental frequencies are proportional. There is a good correlation between the HVSR of the *S*-wave, coda, and pre-event noise portions for frequencies more than 4 Hz. For the frequencies less than 4 Hz, the HVSR of the *S*-wave is higher than the HVSR of coda by a factor of 3. Reflections of *S*-waves from the edges of the unconsolidated sedimentary basin of the ME produce surface waves. The presence of basin-induced surface waves in the coda portion for frequencies less than 3 Hz results in increased amplitude of coda, and as a result, slower decay rate with time implying higher *Q* values. These basin-induced surface waves have a period of 0.5–4.0 s.

1. Introduction

Local site conditions associated with the low-velocity layers near the surface have significant impacts on ground motions by changing the amplitude, frequency content, and duration of seismic waves. Furthermore, evaluation of the site response is one of the main factors to simulate site-specific ground motions and to perform local or site-specific seismic hazard analysis [1,30,33,55]. Several ground motion prediction equations such as those developed for eastern North America (e.g., [5,48,61]) predict the median ground motion intensity measures (GMIMs) for generic rock sites. Then, employing appropriate site-specific amplification factors for the site under study, the GMIM of interest is transferred to the surface from the underneath older, harder, and more competent soil or bedrock. It is assumed that the bedrock would not amplify ground motions. According to the National Earthquake Hazards Reduction Program (NEHRP), the bedrock is defined as the uppermost layer with an average shear wave velocity (V_S) of more than 760 m/s.

To perform site response analyses at different frequencies, we need to have a good understanding of surface geology and dynamic characteristics of the surface layers over the bedrock. The dynamic characteristics of the soil layers are typically correlated with V_S (corresponding to the stiffness), density, and damping ratio of the soil layers, which are characterized by the thickness of different soil layers, degree of compaction, shear modulus, and the age of soil deposits [57].

The site response in sedimentary basins indicates the effect of soil columns and sediments with a low V_S as well as the influence of the basin and underlying bedrock topography [40,70]. Evaluation of site

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response in regions with deep unconsolidated soil layers or sedimentary basins is of particular interest since ground motions can be significantly amplified due to strong impedance contrasts between the surface layers and the bedrock or basement rock at certain frequencies and can cause intense structural damage [7]. Basement rock is defined as a site with no amplification.

There are various approaches to determine site amplification and/or de-amplification factors. The site amplification/de-amplification term in the frequency domain can be numerically estimated using the theoretical methods accounting for the dynamic behavior of soil layers or the shear-wave velocity gradient. These techniques require accurate information about the mechanical and geological features of soil layers. Furthermore, the site transfer function can be experimentally estimated using borehole data, microtremors (background ambient noises), or earthquake recordings. Although analyzing borehole data is one of the most accurate techniques to evaluate the site response, it is not economically justifiable to employ this technique on every site, especially for deep sites. The soil transfer function can be obtained employing the generalized inversion technique, which aids at estimating the source, path, and site responses simultaneously [4,11]. The soil transfer function at a desired site can also be acquired using the spectral ratio of a particular earthquake at that site to a nearby reference rock site characterized as a site free of amplification [15], known as the soil/rock spectral ratio (SRSR) technique. It is worth mentioning that the desired site and the reference rock site should be close enough to share similar path characteristics including the geometrical spreading and attenuation. The main difficulty of this method is to find an appropriate surface outcropping rock site as the reference site that has characteristics of the bedrock below the soil layers at the desired site [59]. As an empirical alternative method, the spectral ratio of the horizontal to the vertical component of a specific event recorded at the desired site can provide a reasonable approximation of the site response, since the near-surface site effects on the vertical component is negligible compared to the horizontal component [5,19,37,45,55,60,63].

The horizontal-to-vertical component spectral ratio (HVSR) technique was first introduced by Nakamura [45] to analyze the characteristics of microtremors which mostly consist of Rayleigh waves. Microtremors are ambient noise composed of high-frequency man-made noise such as those produced by traffic and low-frequency natural noise, for instance, vibrations generated by wind [16]. Then, Lermo and Chávez-García [37] generalized this technique for shear waves to compute the site response deploying earthquake ground motions. The HVSR depicts a suite of peaks corresponding to the shear-wave resonance in a layered velocity structure [36]. Lermo and Chávez-García [37] observed that the site responses obtained from the HVSR technique are in good agreement with the site responses acquired from the SRSR technique. Therefore, they used the peak of the spectrum ratio of the horizontal to the vertical component as an estimation of the first resonant frequency of the site and its amplitude.

By comparing HVSRs with theoretical approximations or numerical simulations, many investigators concluded that the HVSR technique can be used as a first estimate of the site response even at sedimentary basins and extreme local site conditions (e.g., [6,9,10,16,21,23,28,39,44,56]). Note that since the HVSR technique is a first approximation, the accuracy of the higher-mode resonant frequencies and their amplifications has been a challenge. Therefore, this technique is often employed to estimate the first resonant frequency. In addition, comparing the HVSR and the site amplification factor determined from the linear 1-D approximation, several authors concluded that although the location of the peaks representing the resonant frequencies are in fairly good agreement, the peaks' amplitudes are different (e.g., [13,25,32]). Furthermore, a few investigators observed failure of the HVSR technique to estimate the site amplification (e.g., [70]).

In this study, we evaluate the site amplification factor to investigate the effects of unconsolidated sediment with a depth of approximately 1 km within the ME. In this regard, we use the HVSR instead of using the SRSR technique due to the following reasons. First, the basin shape can change the characteristic of ray paths by focusing and defocusing at a site located inside the ME compared to a rock site outside of the basin. Second, the distance between desired stations located in the ME and the nearest reference rock site is relatively long, and thus the assumption of having similar path characteristics for the reference rock site and the desired station may be compromised. Furthermore, the HVSR is an efficient and useful procedure for estimating the fundamental period and site amplification factors of soft soils with a large impedance contrast compared to the underlying bedrock such as is in the ME [8,12,58]. It should be mentioned that the total site response is the combined effects of the site amplification and near-site attenuation, κ_0 [3,14]. However, the purpose of this study is to determine the site amplification not the near-site attenuation.

2. Geology and tectonics of the Mississippi embayment

The ME is an unconsolidated sedimentary basin overlying the New Madrid seismic zone (NMSZ) that is seismically considered as the most active region in the central and eastern United States. The ME is a syncline oriented southward, spreading out from its apex in southern Illinois toward the lower coastal plain of the Gulf of Mexico. Rifting processes have resulted in the synclinal structure [18]. Following that, a relatively large depth of sediments was amassed by erosion of uplifted areas. However, different layers of sediments with different materials (e.g., marine and non-marine sand, silt, clay, etc.) may have been deposited due to different geological processes. From north to south, the depth of the sediments reaches up to 2 km and is about 1 km near Memphis, Tennessee [65,67]. As another result of the rifting processes, reduced thickness of the crust created a zone of weakness that is accompanied by an increased temperature of the crust [62]. This chain of events has been associated with seismic activity in the area, such as 1811–1812 earthquakes ([24]; Brail *et al.*, 1986).

Regarding the geologic-age of near-surface deposits, the ME is divided into two major geological features, uplands and lowlands (see Fig. 1), bounded by the Ozark uplift from the west and the Nashville Dome from the east. The boundaries of these zones are demarcated by significant differences in site responses, which is correlated with the variations in V_S. Large impedance contrast between the Paleozoic bedrocks and the unconsolidated soil deposits result in large P to S conversions [42].

3. Database and data processing

We first collected 2894 three-component broadband seismograms from 274 earthquakes with magnitudes more than 2.5 and hypocentral distances up to 500 km within the NMSZ as the initial database. These events occurred during the period of 2013–2017. Waveforms were recorded by the Cooperative New Madrid Seismic Network (CNMSN) and can be found on the Incorporated Research Institutions for Seismology (IRIS) website. The seismograms were downloaded starting from 85 s before the P-wave arrival until 400 s after the S-wave onset. All recordings were captured at 11 stations equipped with broadband Güralp CMG-40T triaxial broadband seismometers. The data are sampled at 100 samples/sec. All seismometers have a flat velocity transfer function in the frequency range of 0.033–50 Hz. We disregarded any records with hypocentral distances less than 16 km to ensure having enough P-wave window length for analysis. All collected data are visually inspected to discard data with any amplitude anomalies or glitches caused by the instrument. It is worth mentioning that it is not necessary to deconvolve the instrument response from the time series for the HVSR analysis since the instrument transfer function is the same for all three components, and thus it is canceled out by division of the horizontal to the vertical spectra. We selected a high-quality (with a distinguishable P phase from the pre-event noise) subset of the initial