Mapping a NEHRP Site Class Using Multi-channel Analysis of Surface Waves (MASW) Method in Southeast Missouri, USA

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Abstract

Multi-channel surface wave seismic data was acquired at 40 pre-selected sites in the Poplar Bluff study area in southeast Missouri. Additionally, cross-hole seismic data were also acquired at two of these sites. The primary goal was to generate the NEHRP (National Earthquake Hazards Reduction Program) soil amplification map for the Poplar Bluff area using the average shear wave velocity values derived from the multi-channel analysis of surface wave (MASW) data. The secondary goal was to evaluate the accuracy of the MASW estimates. The NEHRP map of the study area generated from these data closely matched the surficial geologic map. Areas mapped on the existing surficial geology map as either Mississippi Embayment lowland soils or Ozark alluvial valley soils have weighted average shear-wave velocity values till 30 m depth ($Vs_{(30)}$) ranging from 182 to 365 m/s, corresponding to NEHRP soil class D. Areas mapped as Ozark upland residual soil, in contrast, have values in the 365 to 762 m/s range, corresponding to NEHRP soil class C.

Keywords: MASW; Shear wave; Surface wave; Earthquake hazard

1. Introduction

Most unconsolidated surficial materials amplify earthquake ground motions, which can affect the stability of structures far from the epicenter of the earthquake. Mapping the areas where soil amplification is likely to occur is a very important objective. Geophysical methods have been used to determine shear-wave velocity for earthquake hazard mapping for many years. In this study, we used the multi-channel analysis of surface wave (MASW) method that was recently developed by the Kansas Geological Survey to determine average shear-wave velocities of soils (Park et al. 1999). The method is similar to the single-channel analysis of surface wave (SASW) method used in civil engineering community, except that the MASW method employs several receivers to detect Rayleigh waves (ground roll).

During summer 2004, multi-channel surface-wave data were acquired at 40 representative sites in the Poplar Bluff study area in southeast Missouri (Figure 1). Cross-hole seismic data was also acquired from boreholes at two of the sites. The primary goal of this study was to use the shear wave velocity estimates derived from the acquired multi-channel surface wave data to generate the NEHRP (National Earthquake Hazards Reduction Program) site class map of the Poplar Bluff area. The resulting map will help Poplar Bluff assess its earthquake shaking vulnerability. The secondary goal was to evaluate the effectiveness of the MASW method to determine the weighted average shear-wave velocity till 30 m depth ($Vs_{(30)}$). $Vs_{(30)}$ is used for the soil classification system adopted by

NEHRP for building-code provisions (Building Seismic Safety Council 2003). To assess the MASW method's effectiveness, MASW-derived shear wave velocity profiles were compared with those derived by the cross-hole seismic data.

2. Site Description

The Poplar Bluff study area was selected for this investigation because it contains one of the larger communities in southeast Missouri that would likely be impacted by a damaging earthquake originating in the New Madrid Seismic Zone. Additionally, the area is situated partially within the Mississippi Embayment alluvial lowlands of southeast Missouri and partially within the Ozark Uplands.

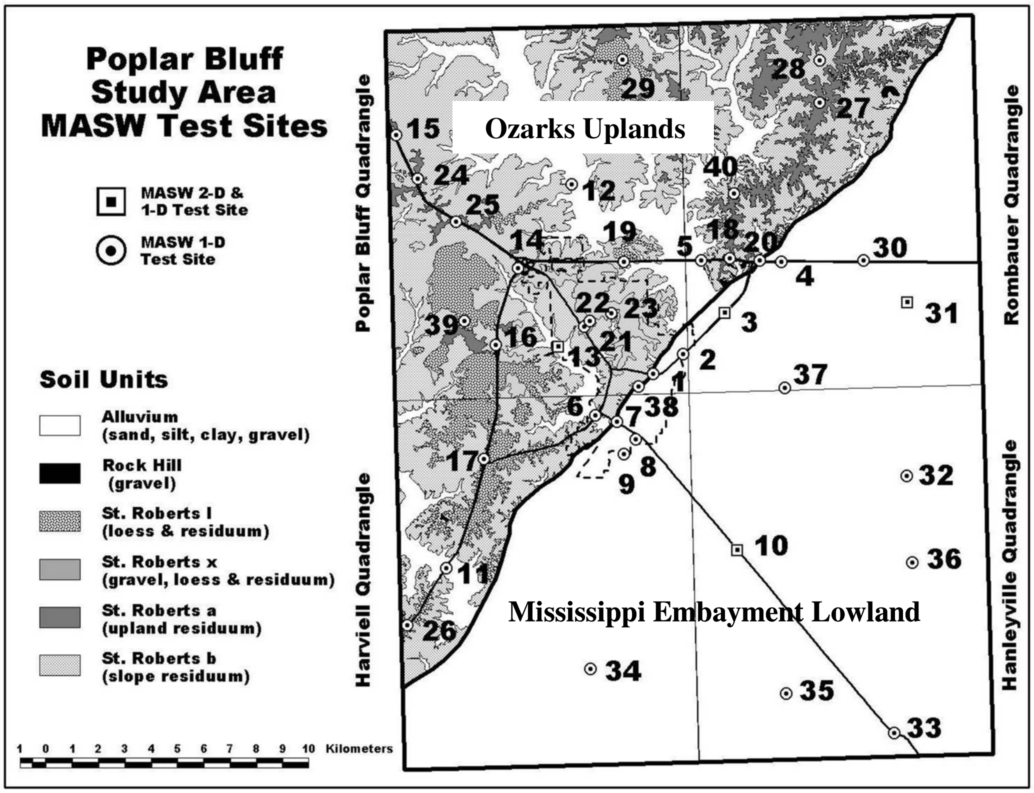


Figure 1: The surficial materials map of the Poplar Bluff study area and MASW testing sites.

The soils, topography and groundwater levels in these two areas are very different. The Mississippi Embayment alluvial lowlands are relatively flat and characterized by alluvial soils composed mostly of sand with some silt, clay and gravel. These alluvial soils are typically 30 to 60 m thick, except immediately adjacent to the Ozark Uplands where the soil is much thinner. The static groundwater level in the lowland is very shallow, typically between 1.5 and 5 m below ground surface. The topography in the Ozarks Uplands, in contrast, ranges from hilly and rugged near stream valleys to gently rolling or nearly level on the upland drainage divides. The residual upland soils are derived from prolonged weathering of the bedrock surface. Intense weathering has dissolved the soluble portions of the bedrock units, leaving behind thick deposits of insoluble clay and large amounts of chert gravel. The residuum varies in thickness from about 12 m to over 60 m, but commonly is about 30 m thick. The groundwater level is usually below the base of the residuum, although small perched groundwater zones occasionally exist within the residuum. Alluvial valley soils within the Ozark Uplands have some characteristics similar to the Mississippi Embayment except these alluvial soils are less extensive, more gravelly and usually thinner.

Two major highways traverse the study area: Route US 60 crosses the area in the east-west direction, and Route US 67 crosses the area in the north-south direction. Both of these four-lane divided highways are critical emergency access routes that need to function efficiently during and after an earthquake in southeast Missouri.

3. Overview of NEHRP site class map

Several investigators have proposed methods for classifying soils and rock based on their site-dependent amplification properties (Will et al. 2000, Borcherdt 1994, Borcherdt et al. 1991, Tinsley and Fumal 1985, Joyner et al. 1981). Joyner et al. (1981), for example, proposed that site conditions could be characterized using the average shear-wave velocity to a depth equal to one quarter of the wavelength of the dominant frequency of interest. However, this method has not been widely used, probably because it is relatively difficult to apply. Borcherdt et al. (1991) simplified the method by demonstrating a correlation between ground motion amplification and the average shear-wave velocity of the upper 30 m of sediment and/or rock. Borcherdt's method has been incorporated into the NEHRP program. The current NEHRP approach categorizes soils as class A, B, C, D, E or F based on their vertical shear-wave velocity profile, thickness and liquefaction potential.

For the purpose of earthquake hazards investigations, according to NEHRP guidelines, the shear-wave velocity of the subsurface must be measured or estimated to a depth of 30 m. The NEHRP shear wave velocity (Vs) assigned to the subsurface at a specific site is calculated using the following formula:

$$\overline{Vs} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{v_{si}}}$$

where:

$\overline{Vs}$ = the NEHRP shear wave velocity,

v_{si} = the shear wave velocity of any layer in m/s,

d_i = the *thickness* of any layer (between 0 and 30 m), and $\sum_{i=1}^{n} d_i$ is equal to 30 m.

Table 1 shows the site soil profile classification system used by NEHRP. Anderson et al. (1996) evaluated the use of the average shear-wave velocity in the upper 30 m. According to their work, attenuation affects ground motions as much as shear wave velocity, particularly for deeper geologic deposits. Although attenuation is not directly included in the current NEHRP provisions, it is accounted for in seismic hazard maps.

4. MASW Data Acquisition and Processing

The MASW method was first introduced into the geotechnical and geophysical community in early 1999 (Park et al. 1999). This seismic method generates a one-dimensional (1-D) vertical shear-wave velocity (Vs) profile (i.e., Vs versus depth) by analyzing Rayleigh surface waves on a multi-channel record. The method utilizes energy commonly considered to be noise on conventional seismic surveys.

Table 1: Soil profile type classification for seismic amplification (FEMA 450, 2003)

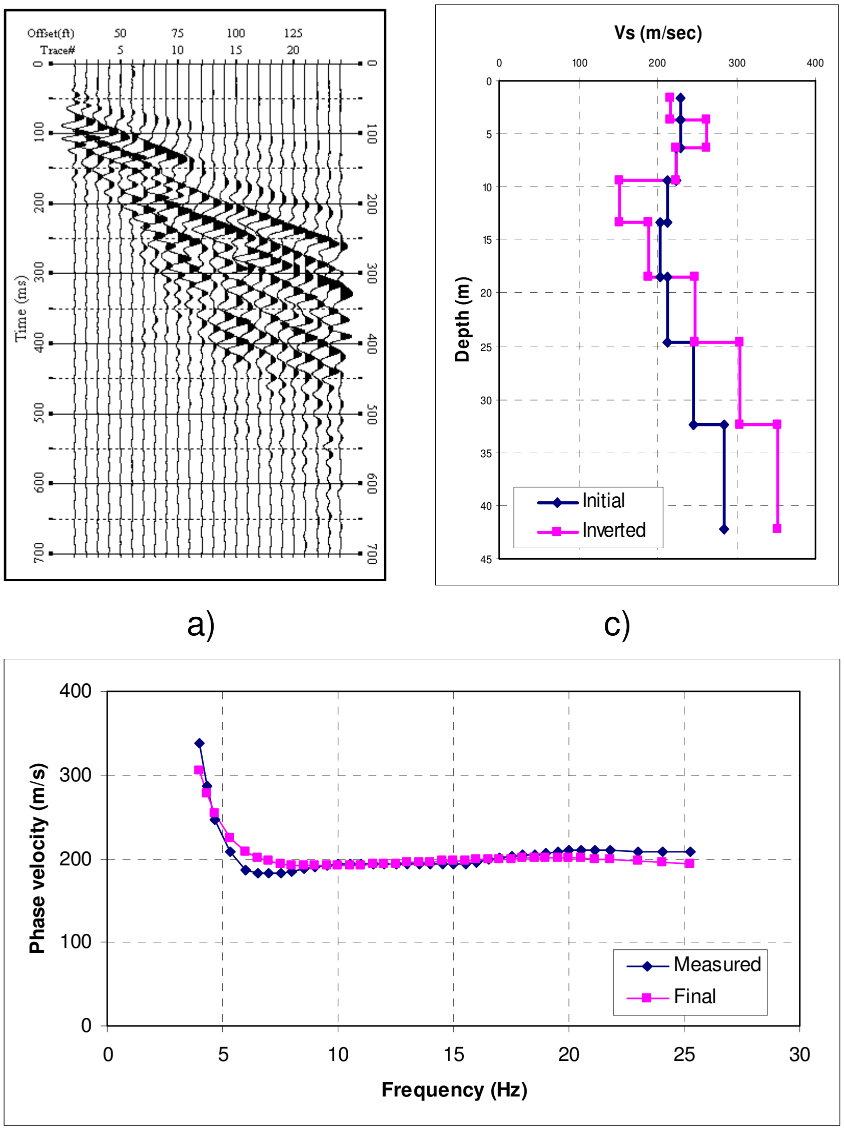
Soil type NEHRP	General description	Average shear wave velocity to 30 m (m/s)
A	Hard rock	> 1500
B	Rock	760 < Vs ≤ 1500
C	Very dense soil and soft rock	360 < Vs ≤ 760
D	Stiff soil 15 ≤ N ≤ 50 or 50 kPa ≤ Su ≤ 100 kPa	180 ≤ Vs≤ 360
E	Soil or any profile with more than 3 m of soft clay defied as soil with PI > 20, w ≥ 40%, and Su < 25 kPa.	≤ 180
F	Soils requiring site-specific evaluations	

N: SPT blow count
Su: Undrained shear strenghth
PI: Plasticity index
w: water content

The acquisition of the 1-D MASW data was similar to conventional seismic data acquisition. In the study area, 24 low-frequency (4.5-Hz) vertical-component geophones, placed at 1.5-m intervals, were centered on each test location. Using lower-frequency geophones (4.5 Hz), have allowed recording surface waves with frequencies as low as 3 Hz, which results in maximum investigation depths of greater than 30m at most of the surveyed sites.

Seismic energy was generated at a minimum offset (source to nearest geophone) of 7.62 m using a 9 kg sledge hammer and metal plate. The minimum offset was determined based on the results of field tests we conducted at several sites in the study region, which showed that the first geophone starts to pick well developed horizontally-travelling plane surface waves at a distance over 7 m. The generated Rayleigh wave data were recorded using the 24-channel engineering seismograph. The total spread length is about 35 m. Park (1999) suggested that the total spread length should be equal or greater than the maximum depth of investigation. This field setup ensured a maximum depth of investigation on the order of 30 m and reduced the body waves and the higher mode surface waves components, which usually dominate over the fundamental mode surface waves at greater offsets.

The acquired Rayleigh wave data were processed using the Kansas Geological Survey software package SURFSEIS. Figure 2 illustrates the processing steps of MASW data. Each set of Rayleigh wave data (24 channels data set for each station location) was transformed from the time domain into the frequency domain using Fast Fourier Transform (FFT) technique. These field-based data were used to generate site-specific dispersion curves (phase velocity versus frequency) for each station location (Figure 2b). The site-specific dispersion curves generated from the field-acquired Rayleigh wave data were then transformed into vertical 1-D shear-wave velocity profiles (MASW shear-wave velocity profile) through an inversion method (Figure 2c), which is explained in detail in Park et al (1999).



a) c)

b)

Figure 2: Processing procedures of MASW data, a) surface wave shot gather, b) the corresponding dispersion curve, and c) the inverted shear wave profile.

The inversion method uses a start model before beginning to search for the answer in an iterative manner. The start model consists of several key parameters: S-velocity (Vs), P-velocity (Vp), density (r), and thickness (H) of the layers in the earth model. Using this set of parameters, the program begins searching for a solution, continuously converging on the most probable values. Vs is the parameter that is the most sensitive and influential to the surface wave phase velocity. The influence of all other types of parameters can usually be neglected as long as they have been reasonably estimated. The start Vs model is approximated from the measured dispersion curve. The initial Vp model is determined using this Vs model and a constant Poisson's ratio of 0.3. A density of 2.0 g/cm^3 is assigned to all layers of the earth model. The maximum depth of investigation is determined based on the wavelength of the longest surface wave; the vertical resolution is dependent on the shortest wavelength. The thickness or layer model is then created by successively increasing the thickness of each layer as its depth increases to the maximum depth of investigation. A start model consisting of ten layers continues to converge towards the optimum solution through an iterative inversion procedure until a minimum root mean square error is reached.

5. Results

The shear-wave velocity ($Vs_{(30)}$) data derived from the MASW measurements in the study area are summarized in Table 2, which shows the classification and averageshear-wave velocity of each test site. (Velocities were averaged over 30 m in accordance with NEHRP guidelines.) The shear-wave velocity values correlate very well with the surficial materials map units. The alluvial lowland soils have lower shear-wave velocities than the upland residual soils. Using the shear-wave velocity data and the NEHRP soil class definitions based on shear-wave velocity, an earthquake soil shaking amplification map of the Poplar Bluff area was made (Figure 3).

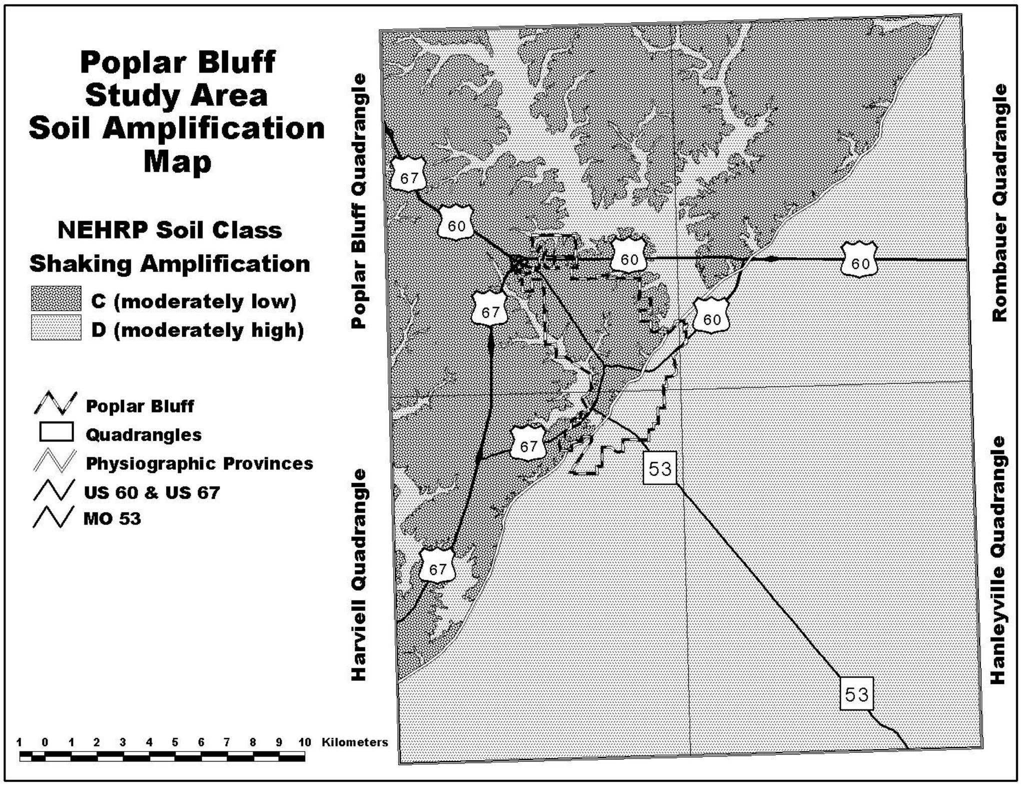


Figure 3: NEHRP site class map of the Poplar Bluff area based on the shear wave velocity measurements

Table 2: Sites and site classifications in the Poplar Bluff area

Site Number	X-UTM8	Y-UTM	Surficial Materials	Vs(30) m/s	Site Class
1	733010	4071050	Alluvium - River & Embayment	251	D
2	734130	4071810	Alluvium - River & Embayment	268	D
3	735720	4073360	Alluvium - River & Embayment	206	D
4	737870	4075270	Alluvium - Embayment	235	D
5	734810	4075310	Alluvium - River	241	D
6	730820	4069500	Alluvium - Creek	187	D
7	731630	4069270	Alluvium - Embayment	198	D
8	732350	4068560	Alluvium - Embayment	224	D
9	731880	4068050	Alluvium - Embayment	235	D
10	736210	4064460	Alluvium - Embayment	235	D
11	725160	4063760	Alluvium - Creek	225	D
12	729900	4078160	Alluvium - River	210	D
13	729395	4072110	Alluvium - Creek	316	D
14	729870	4075060	Residuum	374	C
15	723230	4080020	Residuum	401	C
16	727030	4072150	Residuum	358	D
17	726580	4067880	Residuum	515	C
18	735900	4075390	Residuum	482	C
19	731910	4075280	Residuum	418	C
20	737160	4075325	Residuum	464	C
21	730390	4072840	Residuum	404	C
22	730590	4073045	Residuum	398	C
23	731410	4073330	Residuum	473	C
24	724080	4078380	Residuum	467	C
25	725510	4076770	Residuum	384	C
26	723655	4061620	Residuum	240	D
27	739340	4081240	Residuum	605	C
28	739340	4082850	Residuum	359	D
29	731850	4082860	Residuum	379	C
30	740980	4075310	Alluvium - Embayment	217	D
31	742650	4073760	Alluvium - Embayment	199	D
32	742630	4067230	Sand Dune & Alluvium - Embaym	252	D
33	742160	4057560	Alluvium - River & Embayment	214	D
34	730620	4059960	Alluvium - Embayment	248	D
35	738060	4059060	Alluvium - Embayment	205	D
36	742845	4063990	Alluvium - Embayment	241	D
37	738000	4070540	Alluvium - Embayment	203	D
38	732430	4070580	Alluvium - River & Embayment	297	D
39	725840	4073060	Quaternary/Tertiary Residuum	508	C
40	736060	4077820	Residuum	509	C

The Mississippi Embayment lowland soils and the Ozark alluvial valley soils have shear-wave velocity values in the 182 to 366 m/s range, which puts them in NEHRP soil class D. The Ozark upland residual soils have shear-wave velocity values in the 366 to 762 m/s range which puts them in to NEHRP soil class C. The soils with the lower shear-wave velocity values, or the NEHRP soil class letter farther from A, will experience more earthquake ground shaking than for bedrock due to the wave-amplifying properties of the soil.

6. Conclusions and Recommendations

Forty MASW 1-D shear-wave velocity profiles were collected across the Poplar Bluff Area in southeast Missouri. These shear-wave velocity profiles form the framework for determining the soil classifications of the sediments in the upper northwest part of the Mississippi Embayment. Weighted means for the shear-wave velocities of the upper 30 m of the soil columns were calculated from the MASW shear-wave seismic data. These data were used to classify the soils in the Poplar Bluff area according to the soil/shear-wave velocity classification scheme proposed by NEHRP (Building Seismic Safety Council 2003).

The MASW method is a non-invasive geophysical method to estimate near-surface shear-wave velocity from surface wave energy. The MASW method is cost effective (less expensive than drilling program), fast and reliable and should be considered for generalized evaluation of geological site response models for earthquake hazard studies.

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