

THE EFFECT OF SITE CONDITIONS ON AMPLIFICATION OF GROUND MOTION IN THE ST LOUIS AREA

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ABSTRACT

This study evaluated the likely accelerations and amplifications of long period motion of two historic earthquakes (M 6.6 and 7.8) which emanated from the New Madrid Seismic Zone in the Midwestern United States, using geotechnical data obtained from recent investigations along the lower Missouri River corridor. Our results suggest site amplification between 6X and 13X, depending on magnitude and epicentral distance. Two important factors appear to affect predictions of response spectra and site amplification. The first factor concerns theoretical assumptions about travel path homogeneity. The synthetic earthquakes assume the same input values for each magnitude and the same travel path for each event. A second factor is the fact that only selected soil thicknesses are used in the calculations. However, the greatest thickness of soil lies near the middle of the flood plains, decreasing gradually towards the edges. From the site response analyses, it was determined that when the soil thicknesses varied between 15-25 meters, resonance occurred within the soil. This resonance causes large spectral accelerations and amplifications within the soil column. The large spectral accelerations are attributed to the distinct geologic characteristics of the Central and Eastern North America rocks compared to the other parts of the world. These rocks are older, colder and more indurated, engendering higher travel velocities in rock and less path attenuation. We have confidence that our one-dimensional analyses are valid out in the middle of these gently sloping bedrock depressions, but they may under-predict the site response near the steeply-inclined edges of the flood plain because of incident body waves propagating up through the alluvium.

Keywords: Basin Edge Effects, New Madrid Seismic Zone, Modeling, Amplification

INTRODUCTION

The St. Louis metropolitan area is a densely populated urban zone, bounded by extensive deposits (up to 76 m deep) of unconsolidated sediment (mostly sands) underling well-defined flood plains. The severe curvature of the bedrock channel depressions at their edges may also be sufficient to trap seismic energy and cause incident body waves to propagate through the alluvium as surface waves, producing stronger shaking and longer duration than would be predicted by 1-D analyses. This phenomenon may explain the significant disparities in reported shaking in the channel fills as opposed to bedrock knobs during historic earthquakes. The ground-motions from New Madrid Seismic Zone and Wabash Valley Seismic Zone have not included these basin effects and the scale and resolution of previous studies was of insufficient detail to assess site-specific effects. The national USGS hazard

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maps (Frankel et. al., 1996) do not include the effects of local geologic structure or soil present in the St. Louis Metro Area.

Records and analyses have shown that apart from soil stratigraphy the “geomorphic” conditions (such as those characterizing an alluvial valley) tend to modify the amplitude, frequency content, and duration, as well as the spatial variability of seismic ground shaking. Such basins are usually filled with alluvial, lacustrine, or estuarine sediments that are much less consolidated than the older indurated formations upon which they were deposited. Seismic energy propagates at much lower velocities in these youthful sediments than the underlying rock. Seismic energy that become trapped in sedimentary basins can produce amplitudes up to 50% stronger at intermediate and low frequencies ($f < \sim 1$ Hz) than those recorded on comparable surface materials outside basins, and their significant durations can be twice as long.

Seismic Background

The New Madrid Seismic Zone (NMSZ) is historically recognized for spawning periodic moderate to large size earthquakes. It lies within the upper Mississippi Embayment and extends from northeast Arkansas through southeast Missouri, western Tennessee, and western Kentucky, up into southern Illinois. The NMSZ lies within a 70 km-wide, 200 km-long SW-NE trending graben (known as the Reelfoot Rift) which is interpreted to have formed during an episode of continental rifting that began in late Cambrian time, 523 to 505 million years ago (Hamilton, 1981). The NMSZ dominates central U.S seismicity and, according to Johnson and Nava (1990), has the highest seismic moment release rate of any seismic zone in a stable continental region in the world. Historic seismicity of the region is summarized in Figure 1. Most of the active seismicity is concentrated in the northern embayment, a south-plunging trough of Cenozoic and Upper Cretaceous age sedimentary rocks, which reach a depth of 1 km beneath Memphis, Tennessee. Figure 1 also shows three principal trends of seismicity; two northeast-trending arms with a connecting northwest-trending arm. This pattern of seismicity has been interpreted as a northeast-trending, right lateral strike-slip fault system with a compressional northwest-trending step-over zone (Bakun and Hopper, 2004). A study by Johnston and Schweig (1996) identified seven candidate fault segments within the central fault system of the NMSZ: the Blytheville arch (BA-70 km), Blytheville fault zone (BFZ-55 km), Bootheel lineament (BL-70km), New Madrid West (NW-40 km), New Madrid north (NN-60 km), Reelfoot fault (RF-32 km), and Reelfoot south (RS-35 km), shown in Figure 1.

This region is the source of the 1811–1812 quakes (16 December 1811 **M** 7.6, 23 January 1812 **M** 7.5 and 7 February 1812 **M** 7.8) that occurred early in the recorded history of the American Midwest, which are the largest historic earthquakes in the Central and Eastern United States. The locations of the 1811–12 earthquakes have been resolved with a reasonable degree of certainty for the December 16, 1811 and February 7, 1812 events (Tuttle *et al.* 2002). It has been suggested that the **M** 7.5 event of January 23, 1812 may have occurred much further northeast (about 220 km) of the traditionally accepted location, possibly within the Wabash Valley Fault Zone (Mueller *et al.*, 2004; Hough *et al.*, 2005). Tuttle *et al.* (2002) cites paleoliquefaction evidence that demonstrate four distinct 1811-1812 liquefaction events in the central New Madrid Seismic Zone. These four sequences of liquefaction appear to correspond with the four **M** 7+ events of the 1811-12 sequence, three mainshocks and one large aftersock of the 16 December 1811 mainshock (Johnston and Schweig, 1996; Bakun and Hopper, 2004; Hough *et al.* 2000; Hough, 2002) and these data suggests that all four **M** 7+ earthquakes likely occurred in the New Madrid Seismic Zone, within relatively close proximity to one another (Cramer *et al.* 2005).

Paleoseismic investigations also suggest that the largest of the 1811-1812 earthquakes was not unique in magnitude because paleoliquefaction features provide convincing physical evidence that no less than four similar-size earthquake sequences have occurred in the last 2000 years, with an average recurrence interval of 500 ± 300 years for the New Madrid Seismic Zone events (Tuttle *et al.*, 2002,

2005). Recent studies (Smalley *et al.*, 2005) concluded that the NMSZ is deforming at strain rates of 1 to 2.7 mm yr⁻¹, which is on the same order of magnitude as measurements recorded on tectonic plate boundaries. These measurements are consistent with Tuttle *et al.* (2002), who suggested that the NMSZ produced earthquakes of M 7.6 or higher about once every 500 years. However, other controversial GPS results have been reported elsewhere (Newman *et al.*, 1999).

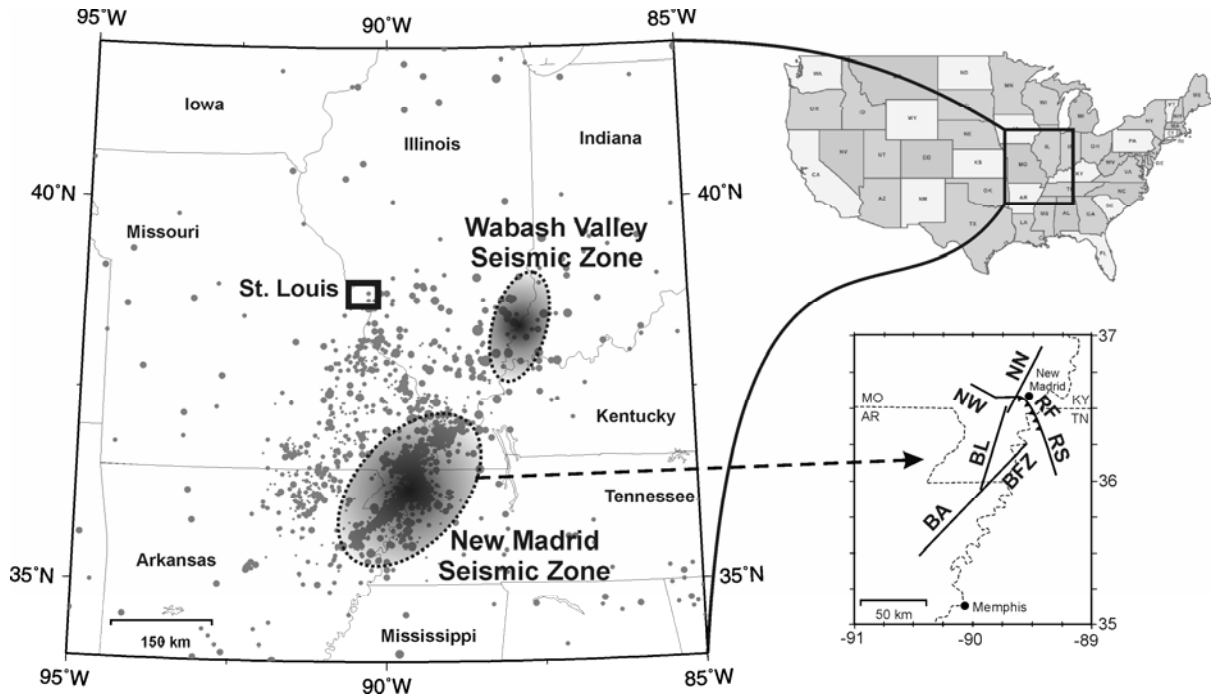


Figure 1. Seismicity of Midwestern United States and the areal extent of the two seismic zones considered in this study: New Madrid Seismic Zone and Wabash Valley Seismic Zone. Dots represent the seismic activity recorded during historic time. The diameters of the circles represent epicenters of earthquakes, with increasing magnitude. Fault segmentation of the NMSZ is given at the right lower corner of the figure. See text for explanation of the various fault segments.

The actual magnitudes of the 1811–1812 New Madrid events remain uncertain for a number of reasons. The 1811–12 earthquakes occurred before the region west of the Mississippi River was settled; so no credible information was recorded west of the River, only east of it. Shaking intensity contours for the 1811–12 events are, therefore, sparse and inconsistent. Another nagging uncertainty arises because of the low rate of seismic activity in the Midwestern U.S., as compared to other regions, like California. The third uncertainty arises out of the extreme impedance contrast between the underlying Paleozoic age bedrock and the unconsolidated alluvial soils filling perennial river channels. The impedance contrast between the Paleozoic age bedrock ($V_s = 3000$ to 4000 m/sec) and Pleistocene age ($V_s = 175$ to 275 m/sec) or Holocene age ($V_s = 150$ to 200 m/sec) is rather severe when compared to other parts of the world. The impedance contrasts causes marked amplification of ground motion, especially low amplitude, long period motions. The severe impedance contrasts in Holocene age alluvium along river valleys likely resulted in an overestimation of the magnitude of the 1811–12 earthquakes because the early American communities were all situated along major rivers (Bakun and Hopper, 2004). Table 1 summarizes the range of estimated magnitudes for the 1811–12 earthquakes, over the past 30+ years.

Table 1: Magnitude estimates from previous studies

	16 December 1811	23 January 1812	7 February 1812	31 October 1895
Nuttli (1973)	7.2*	7.1*	7.4*	-----
Street (1982)	7.0*	7.1*	7.3*	-----
Johnston (1996)	8.0	7.8	7.9	6.6
Hough et. al. (2000)	7.2-7.3	7.0	7.4-7.5	-----
Mueller and Pujol (2001)	-----	-----	7.2-7.4	-----
Bakun et. al. (2003)	-----	-----	-----	6.0
Bakun and Hopper (2004)	7.6	7.5	7.8	-----

*Body magnitudes

A repeat of the M 7+ 1811–1812 earthquakes would have an enormous economic impact on the American Midwest if they occurred today. Our study evaluated the amplification in soil columns due to the changes in basin geometry using two historic earthquake magnitudes and their respective epicentral distances. We selected February 7th, 1812 earthquake, because of its being closest epicentral location to the St Louis area and being highest in magnitude. We also selected the October 31st, 1895 earthquake, because this event has the highest probability of occurrence within the next 50 years. We generated synthetic time histories for the 1812 and 1895 earthquakes using Boore’s (2003) SMSIM code v.2.3 with Atkinson and Boore’s (1995) attenuation relations for the Eastern North America. We then modeled ground motions along the Mississippi and Missouri River flood plains around St. Louis. We evaluated the response spectra values at frequencies of interest and estimated site amplification factors using the 1-D site analysis software SHAKE91.

Geologic Background

The surficial geology of St. Louis varies widely, from thick alluvium in the broad Mississippi River valley (known as the American Bottoms) to thin glacial drift (usually < 15 m) and abundantly exposed Paleozoic bedrock, to thick loess to ice-contact deposits in the “ridged-drift” areas east of the River, in Illinois. The area east of St Louis was eroded twice by continental glaciers advancing from the northeast during the Quaternary Period; first, during the pre-Illinois episode and second, during the Illinois Episode (Willman and Frye, 1970; Grimley et al. 2001). During the Wisconsin Episode (last regional glaciation), the area was not eroded by ice, but did receive glacial meltwater from the north and northeast which deposited silt, sand, and gravel (outwash) in the Mississippi River Valley. Deflation of silty waterlain deposits in the American Bottoms area was triggered by the prevailing westerly winds during the last glaciation, which resulted in a significant thickness of wind-blown loess. The loess is thickest (up to 29 m) at the bluffs immediately east of the broad Mississippi Valley and thins to the east and northeast. The underlying basement strata in this area consists of weathered limestone of predominately Mississippian age, with trace interbedded clay seams, overlain by shales of Pennsylvanian age (Grimley *et al.* 2001). The upper few meters of the modern flood plain are usually comprised of recent lacustrine sediment, mostly compressible silts and clays. Underlying these is a thick sequence of channel sands extending down to the Paleozoic age basement rocks (Goodfield, 1965).

Unit density and shear wave velocity data were correlated from corrected Standard Penetration Tests (SPT) collected at two bridge sites along the Missouri River northwest of downtown St. Louis (Figure 2). We estimated the shear modulus ratio (G/G_{max}), damping ratio, and shear strain, from charts published by the Electric Power Research Institute (EPRI, 1993). These relationships were developed for soils in the eastern and central United States, ranging from gravels and sands to low plasticity sandy clays.

The stratigraphy, thickness, and physical properties of the units comprising the soil cover in the site response analyses are presented in Table 2. The generalized geologic cross-section of the alluvial

materials exposed in the Mississippi River flood plain is provided in Figure 3. Note the spatial variation in thickness and lateral extent common to flood plain sediments.

Table 2: Representative soil profile of lower Missouri and Mississippi River flood plains

Layer	Soil column	Thickness (m)	Vs (m/sec)	Density (g/cm ³)
1	Cahokia Alluvium –clay	5	140	2.0
2	Cahokia Alluvium –sand	14	140	2.0
3	Henry Formation –sand	10	250	2.1
4	Henry formation –sandy gravel	6	270	2.1
5	Mississippian Limestone	984	2900	2.6
6	Paleozoic age bedrock	Half-Space	3600	2.8

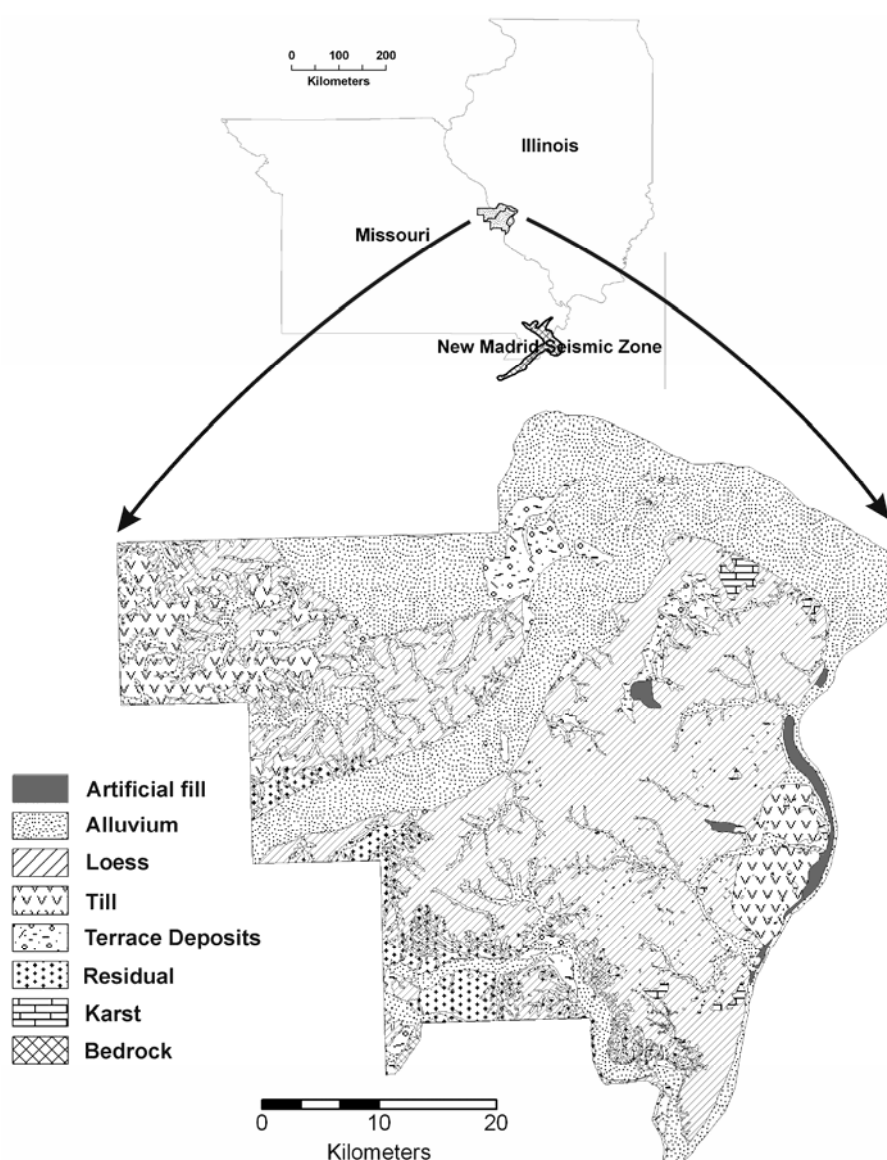


Figure 2. Surficial geology map of St Louis area
RESULTS

The predicted site response at the ground surface was markedly different from the base rock input motion. Three important factors appear to impact site response effects: period migration, wave energy entrapment, and wave amplification. All of the plotted response spectra illustrate migration of the base rock period to longer site periods. This period migration results in a higher potential for constructive interference with the natural period of vibration of long period structures, such as 5 to 8 story tall buildings or bridges. As the period of the seismic energy approaches the structure's natural period of vibration, resonance could cause shaking to be amplified by an order of magnitude. In Table 3 the peak rock and surface accelerations determined from the stochastic method for the two bridge sites are compared.

Table 3: Peak rock and surface accelerations determined from the stochastic method used in the analysis for the two sites in consideration

Historical Earthquakes			Site 1	Site 2
7 February 1812 Earthquake (Magnitude 7.8)	Distance to Epicenter =		315 km	275 km
	Acceleration (g)	Rock	0.026	0.035
		Surface	0.076	0.09
31 October 1895 Earthquake (Magnitude 6.6)	Distance to Epicenter =		260 km	210 km
	Acceleration (g)	Rock	0.009	0.017
		Surface	0.026	0.035

Figure 4 compares the predicted site accelerations and amplifications for the two historic events: M_w 7.8 in February 1812; and M_w 6.0 in October 1895, at four distances between 210 to 315 km (see Table 3). The amplification of seismic energy through a soil column is greater in lower magnitude earthquakes because the weaker ground motions are of insufficient magnitude to trigger an inelastic response (nonlinear soil effects), which causes substantive damping of incoming seismic energy. This phenomenon results in greater amplification of incoming seismic energy for smaller magnitude events.

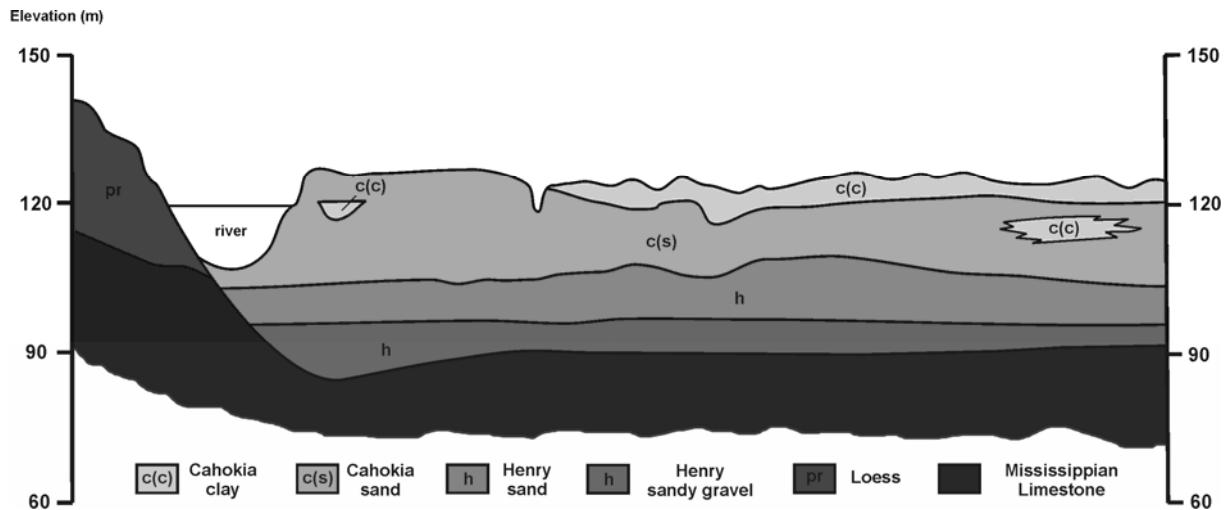


Figure 3. General geologic cross-section of the modern Mississippi River valley (based on Grimley and Phillips, 2006)

In our 1-D analyses, the moment magnitude of the historic and synthetic earthquakes does not appear to significantly affect site amplification at longer periods because the resonant frequency of the soil cover controls the dynamic response. However, at shorter periods (< 0.50 s), damping exerts increasing control on the behavior of the soil cover, and smaller magnitude earthquakes appear

incapable of inducing large strains, typically exhibiting much higher site amplifications than large magnitude earthquakes ($M_w \geq 7.5$). At longer distances, the amplitude of seismic waves is lower, which induces lower strains; therefore, damping is not as significant (see Figure 4).

The entrapment of wave energy observed in the response spectra at the ground surface within the soil profile is illustrated by the “double peaks” shown in Figures 4. Entrapment occurs when seismic energy is reflected between the ground surface and the bedrock. When the reflected energy reaches the surface, it increases the spectral acceleration by combining with original motions still propagating through the soil cover. The “double peak” response phenomena was observed in all of the synthetic events at long epicentral distances (> 70 km), between magnitudes M_w 6.6 and 7.8.

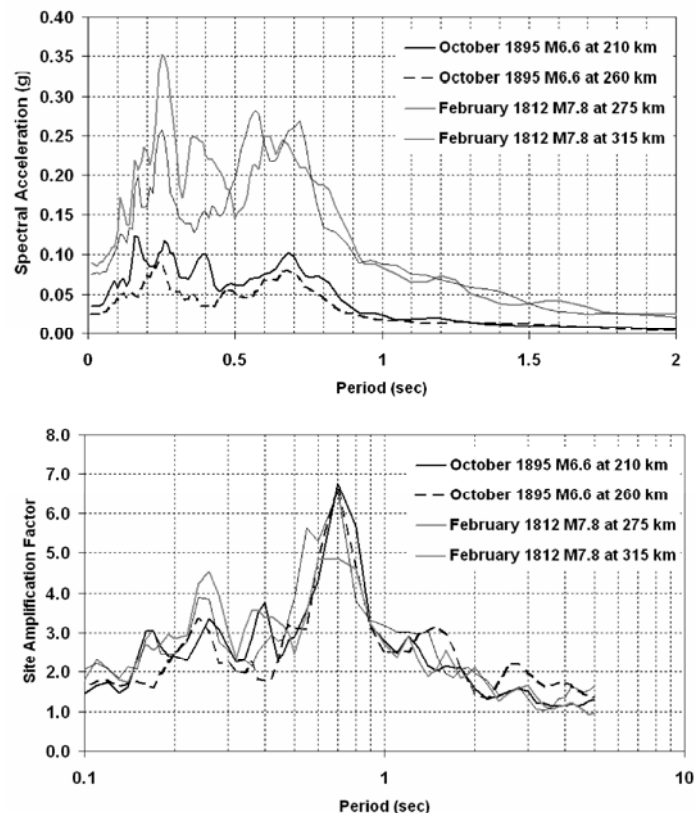


Figure 4. Comparisons of spectral accelerations and amplifications for historic quakes emanating from the New Madrid Seismic Zone for an idealized 35 m thick sediment .

Figure 5 compares the predicted site accelerations at distances between 215 and 275 km, for a moment magnitudes of 6.6 and 7.5, respectively, and compares the amplification factors for the same magnitude earthquakes. From Figures 4 and 5 it can be appreciated that the principal factors controlling site amplification at these sites appears to be: 1) the magnitude of the earthquake; 2) the impedance ratio between bedrock and the soil cover, and; 3) the thickness of the soil cover. A surprising result is that the epicentral distance is not one of the controlling factors in site amplification. The data summarized in Figure 5 and 6 suggest there is little difference in site amplification generated by earthquakes in the north or south ends of the New Madrid Seismic Zone. This is because of the low energy attenuation in the stiff and relatively continuous Paleozoic basement rocks underlying Eastern North America (ENA) (Cramer, 2007). The amplitude of vertically propagating shear waves increases as they pass from high-velocity Paleozoic-age rock ($V_s = 3000$ to 4000 m/sec) to the low-velocity Holocene age soil cover ($V_s = 150$ to 200 m/sec) due to the conservation of energy. The site amplification also increases because of wave energy resonance within the soil cover, due to the

marked impedance contrast at the bedrock/soil cover boundary. We also noticed a shift in the response peak from 0.4 s towards 1.0 s, illustrated in Figure 5. This shift suggests a ground-motion level (magnitude) when nonlinear behavior of the excited soils begins to control site response.

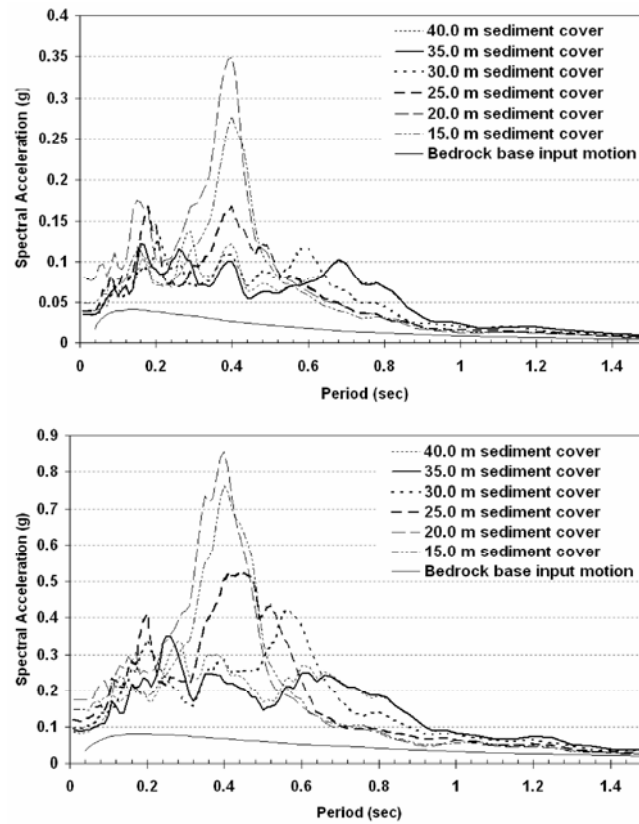


Figure 5. Comparisons of spectral accelerations of historic earthquakes (generated synthetically) emanating from the New Madrid Seismic Zone for varying thicknesses of soil cover. The upper figure shows these comparisons for magnitude 6.6 earthquake at a distance of 210 km while the lower figure shows these comparisons for magnitude 7.8 at a distance of 275 km. Note different scales on the two plots.

The unusually high spectral accelerations at great distance can be explained by the unique geologic characteristics of the ENA Craton. Spectral accelerations remain high at significant distances because of the distinct geologic characteristics of ENA. ENA rocks are much older, colder, more indurated, and less deformed than most tectonically-active parts of the world, such as Western North America (WNA). For these reasons, ENA basement rocks consistently exhibit much higher transmission velocities. The unique geology of the ENA dictates the low path attenuation of seismic waves with distance (Cramer, 2007).

The thickness and stiffness of the soil cover directly affect the predominant periods of vibration of the ground. As the depth of the soil cover increases, or the soil becomes less consolidated (lower value of V_s), the fundamental site period increases in duration. This effect can be seen in Figure 6 for M 6.6 at a distance of 210 km and M 7.8 at a distance of 275 km from the source. The data presented in Figure 6 suggests that as the thickness of the soil column increases, the fundamental site period also increases. In all these results the response accelerations also appear to decrease with increasing soil thickness. From Figures 5 and 6 it can be appreciated that the response accelerations and amplifications are largest when the soil cover is between 15 m – 25 m thick. At these thicknesses the

resonance effect can be appreciated. The analyses consistently showed that the peak acceleration and periods are markedly different for different soil thicknesses.

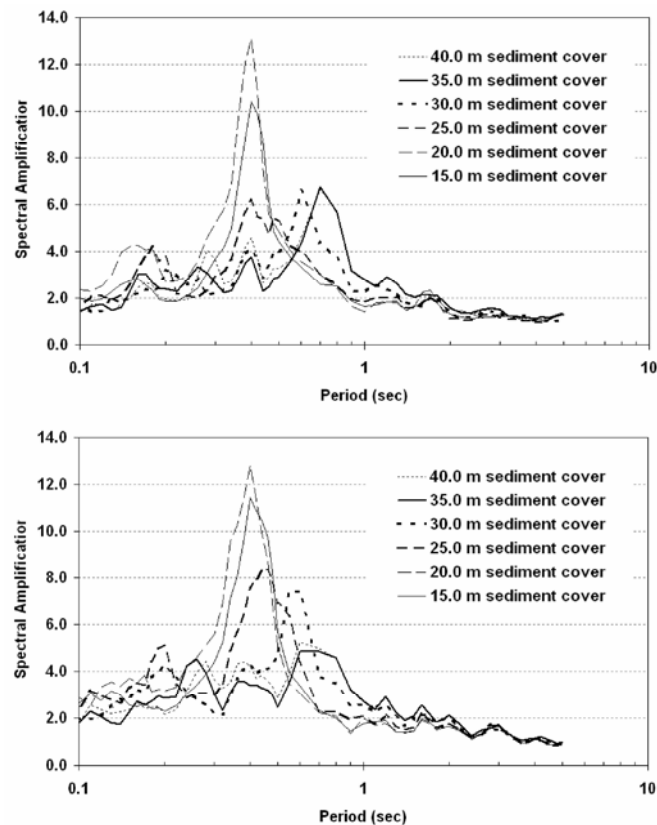


Figure 6. Thickness of soil cover versus spectral amplification for synthetic earthquakes emanating from the New Madrid Seismic Zone. The upper figure shows the effect of soil thickness on the spectral amplification for a M_w 6.6 earthquake at a distance of 210 km. The lower figure shows the same effect for a M_w 7.8 earthquake at a distance of 275 km.

CONCLUSIONS

This study found that two principal factors affected predictions of response spectra and site amplification in the St. Louis area. The first factor concerns the theoretical assumptions about travel path homogeneity. The synthetic earthquakes we employed assume the same input values for each magnitude and the same travel path for different magnitude events. However, the properties of the seismic waves in actual earthquakes are usually different, due to the unique geological conditions and lithologies traversed by their travel paths. A second concern arises from the fact that only selected soil thicknesses were used in the sensitivity analyses. Well records indicate that soil (alluvial unconsolidated soft material) reaches its maximum thickness near the center of the modern flood plain along the lower Missouri River, decreasing gradually towards the edges. This will effect the characteristic site period across the flood plain and, thus, resonance values within the soil cover. This study suggests that soil thicknesses between 15-25 meters cause resonance. This resonance causes large spectral accelerations and amplifications (between 6X and 13 X) at the ground surface. The large spectral accelerations are attributed to the distinct geologic characteristics of the bedrock basement in Eastern North America, which is geologically old and undisturbed as compared to the other parts of the world. These waves could produce stronger shaking locally, with increased durations than would be predicted by one-dimensional analyses which assume vertically-propagating shear waves (common to the western U.S.). We have confidence that our one-dimensional analyses are valid where the

bedrock surface is gently sloped, but this method may under-predict the site response near the edges of the Missouri and Mississippi River flood plains, which commonly support bedrock escarpments up to 50 meters high.

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