Development of Seismic Ground Motions at Four Bridge Sites in the State of Illinois

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Introduction

The Applied Technology Council (ATC), in a joint venture with the Multidisciplinary Center for Earthquake Engineering Research (MCEER), has recently completed a project to develop recommended specifications and commentary for the seismic design of highway bridges (National Cooperative Highway Research Program (NCHRP) Project 12-49). These recommended specifications are being considered by the American Association of State Highway and Transportation Officials (AASHTO) for possible incorporation into the AASHTO LRFD Bridge Specifications (Capron et al., 2001).

Among the changes proposed to current bridge seismic design practice are the following (Capron et al., 2001):

- Performance Criteria – Performance-based design criteria will address two levels of performance objectives: one based on an earthquake with a 50% probability of exceedance in the 75-year design life of a bridge; and the second based on an earthquake with a 3% probability of exceedance in the 75-year bridge design life.
- Service and Damage Levels – Two service level definitions are proposed:
    1. "Immediate" which indicates full access to normal traffic following the earthquake; and
    2. "Significant Disruption" which indicates limited access where bridges may require shoring and/or possible replacement.

Bridges should be designed to satisfy the performance criteria provided in Table 1. According to the NCHRP Project 12-49 or the Recommended LRFD Guidelines for the Seismic Design of Highway Bridges: Part I Specifications (hereafter referred to as NCHRP Specs), bridges shall be designed for the life safety level of performance. Life safety in the Maximum Credible Earthquake (MCE) event means that the bridge should not collapse, but complete or partial replacement may be required. The adopted hazard maps for the Rare Earthquake or MCE are the 3% probability of exceedance in 75 years developed by the United States Geological Survey (USGS) research team (Frankel et al., 1996). It should be noted that the USGS national hazard maps are produced for a 2% probability of exceedance in 50 years, which is in effect the same as a 3% probability of exceedance in 75 years. Therefore, the MCE corresponds to the occurrence of an earthquake with a 2% probability of exceedance in 50 years. A 2% probability of exceedance in 50 years corresponds to a return period of approximately 2500 years.

Table 1. Design Earthquakes and Seismic Performance Objectives.

		Performance Level	
Probability of Exceedance For Design Earthquake Ground Motion		**Life Safety**	**Operational**
Rare Earthquake (MCE) 3% PE in 75 years / 1.5 Median Deterministic	Service	Significant Disruption	Immediate
	Damage	Significant	Minimal
Expected Earthquake 50% PE in 75 years	Service	Immediate	Immediate
	Damage	Minimal	Minimal to None

Adoption of the proposed NCHRP Specs may result in a significant increase in the level of earthquake forces for bridges located in the Central United States as opposed to the current AASHTO specifications. As an example, Figure 1 illustrates the response spectra for the 3% probability of exceedance in 75 years (NCHRP Specs) and the 15% probability of exceedance in 75 years (current provisions) for a site in Cairo, Illinois. These findings as presented in Figure 1 strongly suggests that there will be an increase of about 2.5 to 3 times in the level of seismic design forces if the NCHRP Specs are adopted for this site.

The purpose of this study is to regenerate acceleration coefficients at four sites in the State of Illinois for both bedrock and ground surface levels using existing source paths and site models, and attenuation relationships supplemented by new developments to produce synthetic time histories, response spectra values at frequencies of interest, uniform hazard spectra, and site amplification factors.

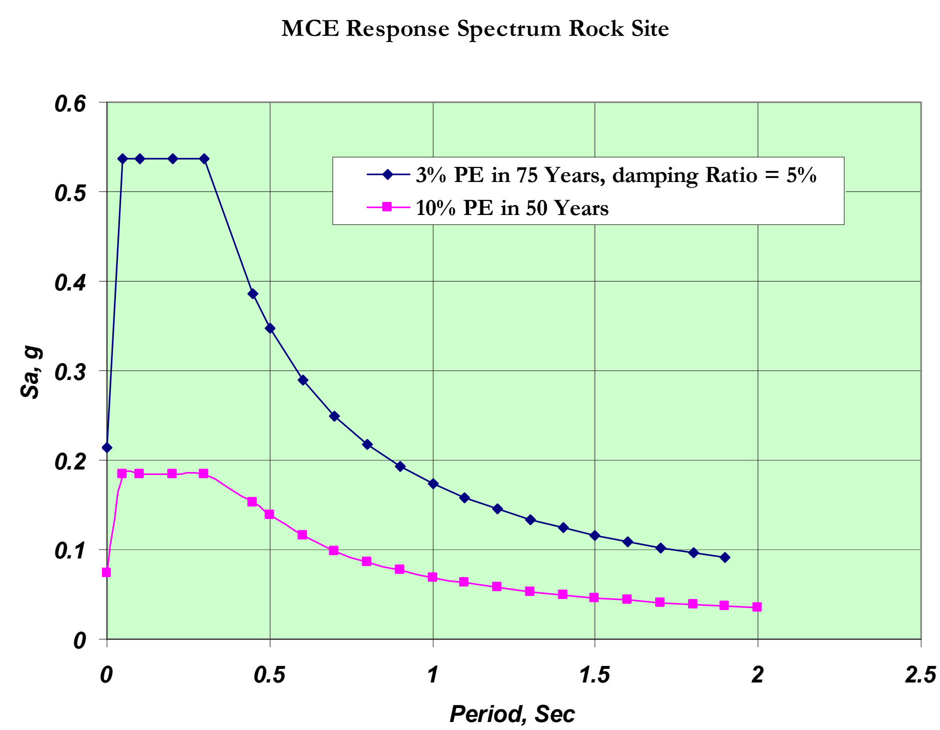
The input zip-code is 62914.

ZIP CODE	62914
LOCATION	37.0075 Lat. -89.1786 Long.
DISTANCE TO NEAREST GRID POINT	2.0811 kms
NEAREST GRID POINT	37.0 Lat. -89.2 Long.

Probabilistic ground motion values, in %g, at the Nearest Grid point are:

	10%PE in 50 yr	5%PE in 50 yr	2%PE in 50 yr
PGA	22.414881	62.700871	166.828598
0.2 sec SA	41.173191	118.358902	341.467712
0.3 sec SA	29.606319	92.532791	281.704193
1.0 sec SA	9.099039	29.525511	116.981697

(a)



(b)

Figure 1. Response spectrum for a site in Cairo, Illinois: (a) Probabilistic ground motion values generated by USGS, (b) Response spectra for 3% and 15% probability of exceedance in 75 years.

Methodology and Scope

Two major tasks were identified in the submitted proposal to accomplish the objectives of this research project:

1. Develop procedures to generate horizontal bedrock motions at four bridge sites in Illinois, from a seismologically based model, due mainly to shear waves generated from seismic sources affecting the sites of interest. The seismologically-based model will include effects of attenuation (Atkinson and Boore 1995; Toro et al. 1997; Frankel et al. 1996; Pezeshk, et al., 1998; Somerville, et al., 2001; and Campbell and Bozorgnia, 2003), characteristics of the source zone, recurrence interval (1000, and 2500 years), and seismotectonic setting of the New Madrid seismic zone, Wabash zone, and other potential seismic sources in the region. Recurrence intervals of 1000 and 2500 years were considered based on the information from the "Federal Highway Administration (FHWA) Mid-America Ground Motion Workshop in Collinsville, Illinois" that suggested 1000 year return periods be considered as options in replacing the current 2500 year return period.
2. Generate peak ground accelerations, 1-second response spectrum accelerations, and 0.2-second response spectrum accelerations for the selected four sites by transmitting the seismic waves at the bedrock through soil.

Each major task includes several sub-tasks as described in more detail below.

Task 1 – Development of Horizontal Bedrock Motions

Task 1 consists of development of procedures to generate horizontal bedrock motions for four bridge sites in Illinois based on the latest available information. This task will include several sub-tasks as described briefly below.

Task 1.A – Identification of Seismic Source Zones

A detailed literature search was performed to identify seismic sources that will be used to characterize seismicity in the New Madrid region and any other potential seismic sources in the region including the Wabash region. The research publication by Van Arsdale and Johnston (1999) was used to define seismic sources. In addition, the report by Toro and Silva (2001) was used to identify seismic sources and to quantify the rates of occurrence and maximum magnitude for various sources. Recent and ongoing research under the auspices of the Mid-America Earthquake Center (MAEC) was considered with specific attention to seismic sources and parameters that are relevant to Illinois.

We believe that the parameters used by Toro and Silva (2001) and Van Arsdale and Johnston (1999) are more suitable for the study region (see Figure 2). The focus of this project was the state of Illinois; therefore, all attentions was focused on seismic sources and parameters that are prevalent to Illinois. Figure 2 shows the New Madrid seismic zone and other seismic sources used by Toro Silva (2001) and also used in this study. Figure 3 shows the background seismic sources used by Toro and Silva (2001) and were also included in this study.

Task 1.B – Evaluation of Attenuation Relationships and Occurrence Rates

Seismic attenuation relationships and occurrence rates are key input parameters for generation of bedrock ground motions. The following attenuation equations were used using equal weights: Atkinson and Boore (1995); Toro et al. (1997); Frankel et al. (1996); Pezeshk, et al. (1998); and Campbell and Bozorgnia (2003).

Task 1.C – Generation of Artificial Earthquakes and Bedrock Motions

In this task, maps of appropriate scales was used to determine the seismic hazard and the probabilistic consistent magnitude and epicentral distance. The consistent magnitude and epicentral distance as well as attenuation relationships and occurrence rates determined in Task 1.B was used to generate artificial earthquakes with a corresponding bedrock time history at each of the four sites considered. The computer program SMSIM (Boore 2003) was used to generate artificial time histories for this study. Spectral values were generated for 5 Hz (0.2 seconds), 1 Hz (1 second), and peak rock accelerations for return periods of 1000 and 2500 years at the selected four sites.

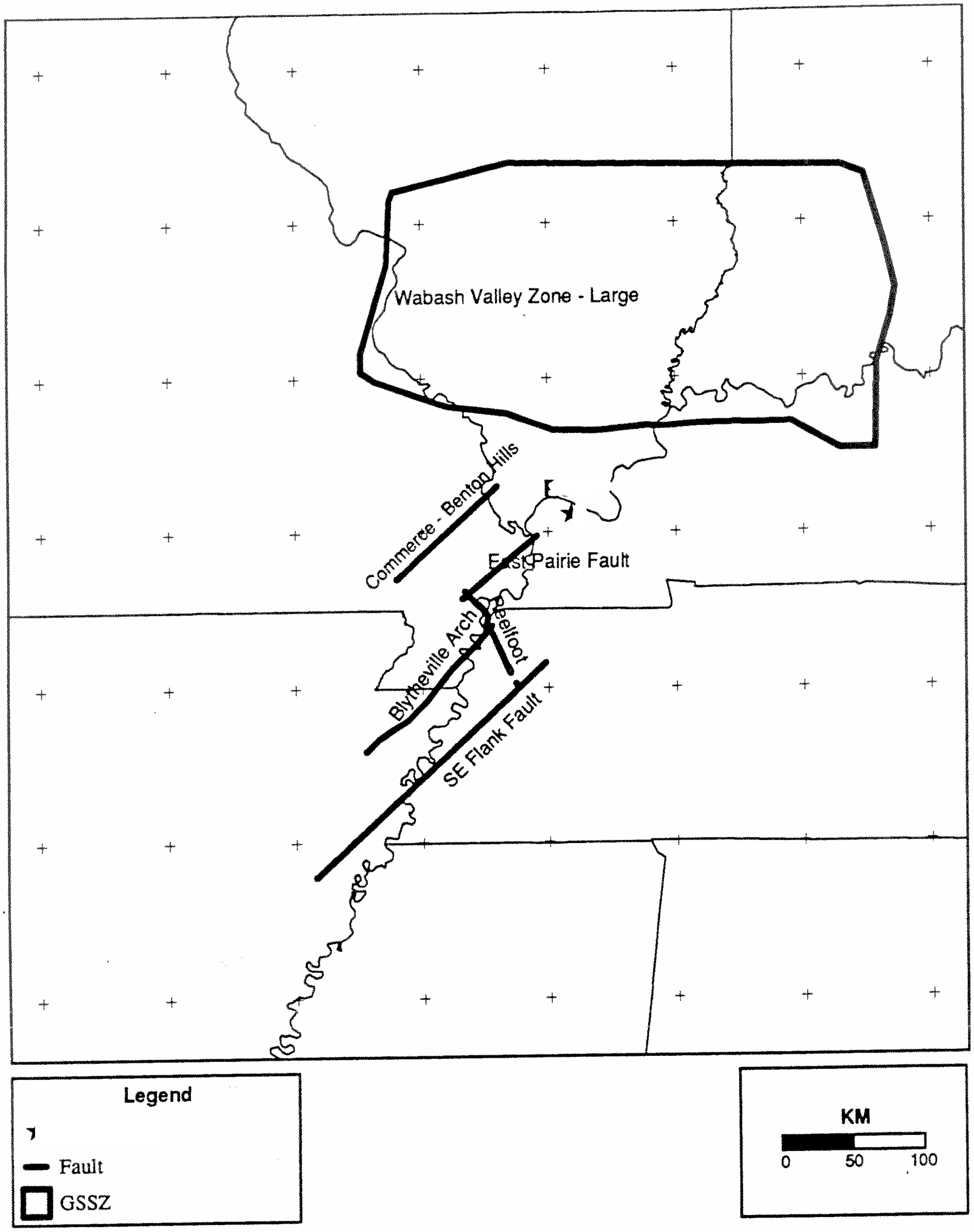


Figure 2. The New Madrid Seismic Zone and other Seismic Sources used by Toro Silva (2001).

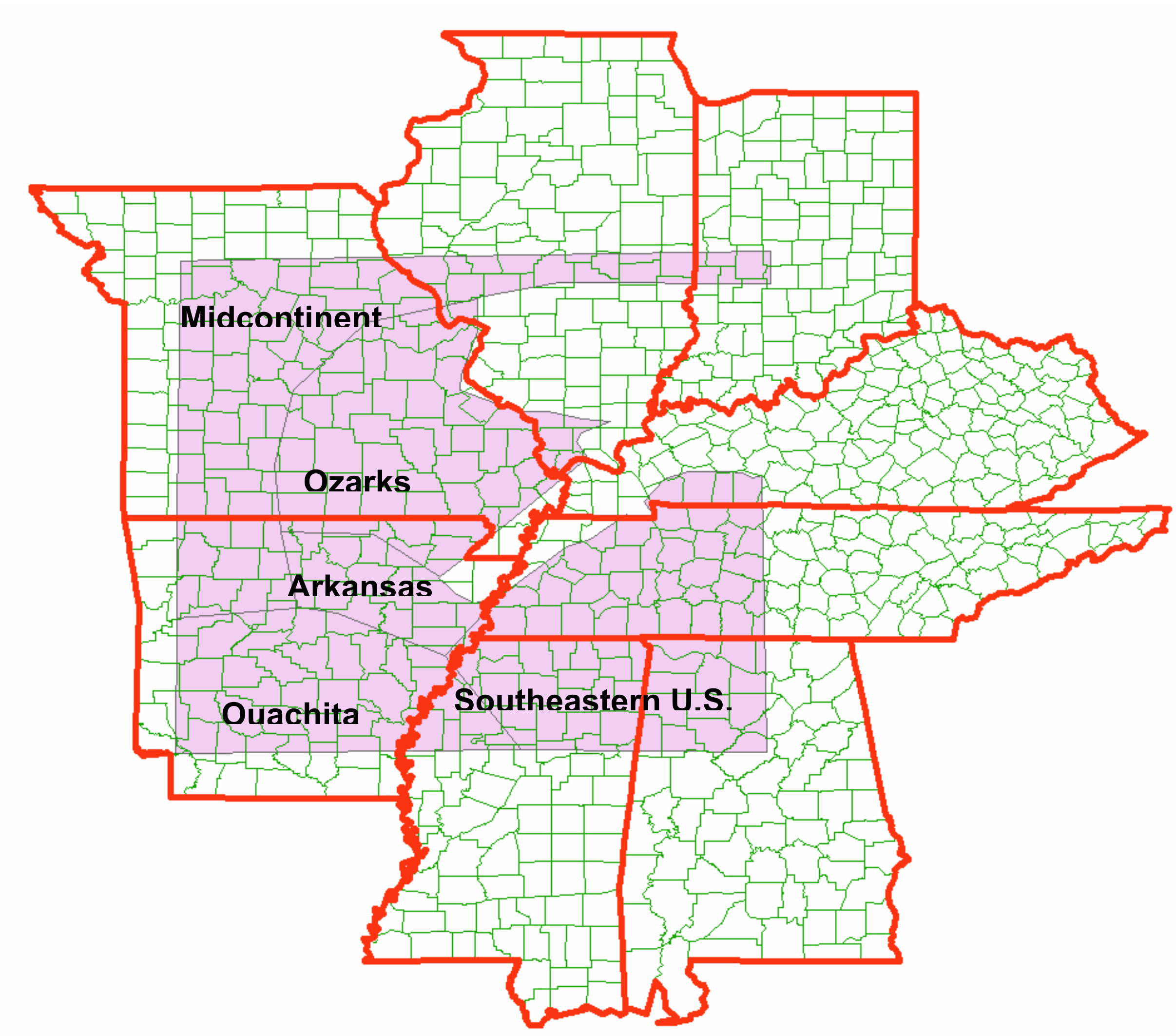


Figure 3. Background Seismic Sources (Adopted from Toro and Silva (2001)).

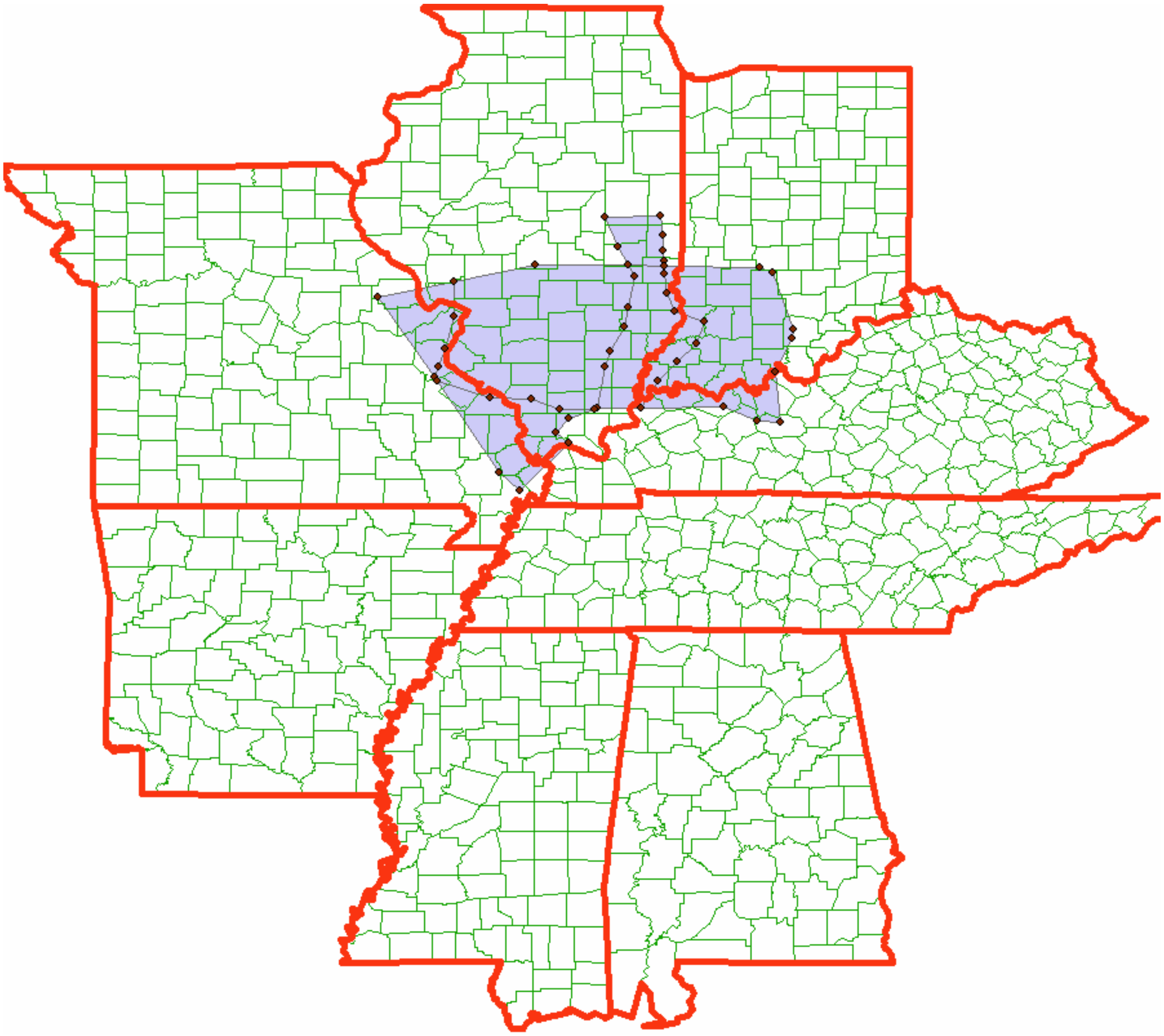


Figure 4. Three Zones used to Represent Wabash Seismic Zone (Adopted from Toro and Silva 2001)).

Task 2 – Site Response Analyses

Task 2.A – Site Studied

Site-specific studies were performed for four bridge sites in Illinois:

- Bridge 1. Located in Pulaski County (37.200^{o}N, 89.152^{o}W)
- Bridge 2. Located in Johnson County (37.433^{o}N, 88.869^{o}W)
- Bridge 3. Located in St. Clair County (38.588^{o}N, 89.912^{o}W)
- Bridge 4. Located in Madison County (37.283^{o}N, 89.150^{o}W)

Locations of these bridge sites are shown in Figure 5 and Figure 6.

Task 2.B – Determination of Acceleration Coefficients

Site response analyses were performed to obtain representative response spectra at the ground surface based on the propagated NEHRP B-C boundary time histories and soil properties obtained from soil boring information at each bridge. The shear wave velocities for the upper soil strata were obtained from standard penetration test (SPT) using the procedure outlined in Pezeshk et al. (1998) and Wei et al. (1999). The shear wave velocities for the remaining depth of soil/rock to the bottom of the soil boring were determined based on the shear wave velocity profile as outlined in Pezeshk et al. (1998) and Romero and Rix (2001). The shear modulus, G_{max}, corresponding to very small shear strain (lower than about 3×10^{-4} percent) was determined based on the in-situ shear wave velocities. The shear modulus degradation curves and damping ratio curves used were taken from Pezeshk et al. (1998).

To determine a better estimate of site characterization for Bridges 1 and 4, Mr. Bob Bauer of Illinois Geological Survey was contacted. Mr. Bauer identified the Weldon Wells borehole (SS# 13430) in Section 15 of T15S, R1W closest to bridge 1 and bridge 4 sites. For bridges 1 and 4, the boring logs provided at the bridge site were used for the upper strata. The Weldon Wells borehole is used for depth for the remaining depth of soil/rock to the bottom of the soil boring at the bridge sites.

Once the required input data are collected, site response analyses were performed for the four selected sites using a commercial site response software. Utilizing these data, the program SHAKE91 (Idriss and Sun, 1992) was used to conduct equivalent linear seismic response analyses of the assumed horizontally layered soil deposits. Among the information produced by SHAKE91, the relevant data for this study consisted of the response spectra at the surface for the 0.2 second and 1.0 second spectral accelerations and the surface time histories.

The spectral accelerations at 0.2 second and 1.0 second were determined from the appropriate response spectrum based on the attenuation equations used in the probabilistic seismic hazard analysis (PSHA). Using these values, the smooth, uniform hazard response spectrum at the ground surface was generated for design ground motions with 1,000 and 2,500 year-return periods and damping of 5 percent.

Summary of Results

Table 2 provides three set of acceleration coefficients: (1) USGS 1996 acceleration coefficients, (2) Toro and Silva (2001) acceleration coefficients, and (3) acceleration coefficients from this study. Data in Table 2 have also been illustrated in Figures 5 and 6. From Table 2 and Figures 5 and 6, one can observe that the USGS 1966 and this study have comparable acceleration coefficients when a 2500-year return period is considered. However, in general the acceleration coefficients determined in this study are lower than the USGS acceleration coefficients. Furthermore, Toro and Silva acceleration coefficients, which are for rock sites, are much smaller than the other two studies. In general, this study results in higher acceleration coefficients than USGS 1996 acceleration coefficients for a 1000-year return period ground motions. No comparisons have been made to the USGS 2002 acceleration coefficients because NCHRP specs are based on the USGS 1996 not the 2002 hazard maps.

The site amplification factors for 0.2-second and 1.0-second spectral for 2% probability of exceedance in 50 year ground motions are provided in Table 2. It should be noted that both bridge 1 and bridge 4 are located on a NEHRP Site Class D with soil column at bridge 4 having a much lower average shear-wave velocity in the top strata than bridge 1. Bridge 3 is located on soft soil and is identified as site class E. The reason for having a lower site coefficient factor for short period spectral response and a higher site coefficient for long period spectral response for bridge 3 is perhaps because of a deep soil column (Park, et al. 2004).

Future Research

Recently, another software packages named DEEPSOIL has been developed by professor Hashash of the University of Illinois and his students (Hashash and Park, 2001; Hashash and Park, 2002). The software package DEEPSOIL, which considers the full nonlinear behavior of soil, is based on new research being conducted for the Mid-America Earthquake Center (MAEC). It is believed for sites that soil columns to the bedrock is deep the computer program SHAKE91 might not provide the accurate representation of deep soil columns (Park, et al. 2004). As part of this work, we would like to propose for a future work to consider using the computer package DEEPSOIL and compare the results with SHAKE91 results.

Table 2. Summary of Results

	Return Period (Years)	Coordinates		National Hazard Maps			Toro and Silva (2001)			This Study		
		Latitude	Longitude	PGA	0.2 sec	1 sec	PGA	0.2 sec	1 sec	PGA	0.2 sec	1 sec
Bridge1	2500	37.2	89.152	1.533	3.161	0.919	0.450	0.900	0.250	1.320	2.434	0.607
	2500 - USGS 2002			1.737	3.330	1.114						
	1000			0.555	1.102	0.264				0.886	1.542	0.460
	Site Coefficient				1.000	1.500					1.031	2.756
	Ground Surface				3.161	1.379					2.510	1.673
Bridge 2	2500	37.433	88.869	0.921	1.750	0.506	0.330	0.600	0.180	0.835	1.685	0.331
	2500 - USGS 2002			0.955	1.766	0.486						
	1000			0.420	0.847	0.203				0.530	0.909	0.210
	Site Coefficient				1.000	1.300					1.390	1.169
	Ground Surface				1.750	0.658					2.342	0.387
Bridge 3	2500	38.588	89.912	0.327	0.626	0.192	0.170	0.330	0.075	0.374	0.579	0.148
	2500 - USGS 2002			0.334	0.640	0.181						
	1000			0.184	0.376	0.103				0.177	0.370	0.069
	Site Coefficient				1.337	2.161					0.694	2.865
	Ground Surface				0.837	0.415					0.402	0.424
Bridge 4	2500	37.283	89.150	1.433	2.655	0.769	0.450	0.900	0.250	1.290	2.153	0.508
	2500 - USGS 2002			1.592	2.930	0.887						
	1000			0.555	1.110	0.264				0.880	1.338	0.377
	Site Coefficient				1.000	1.500					0.688	2.598
	Ground Surface				2.655	1.154					1.480	1.320

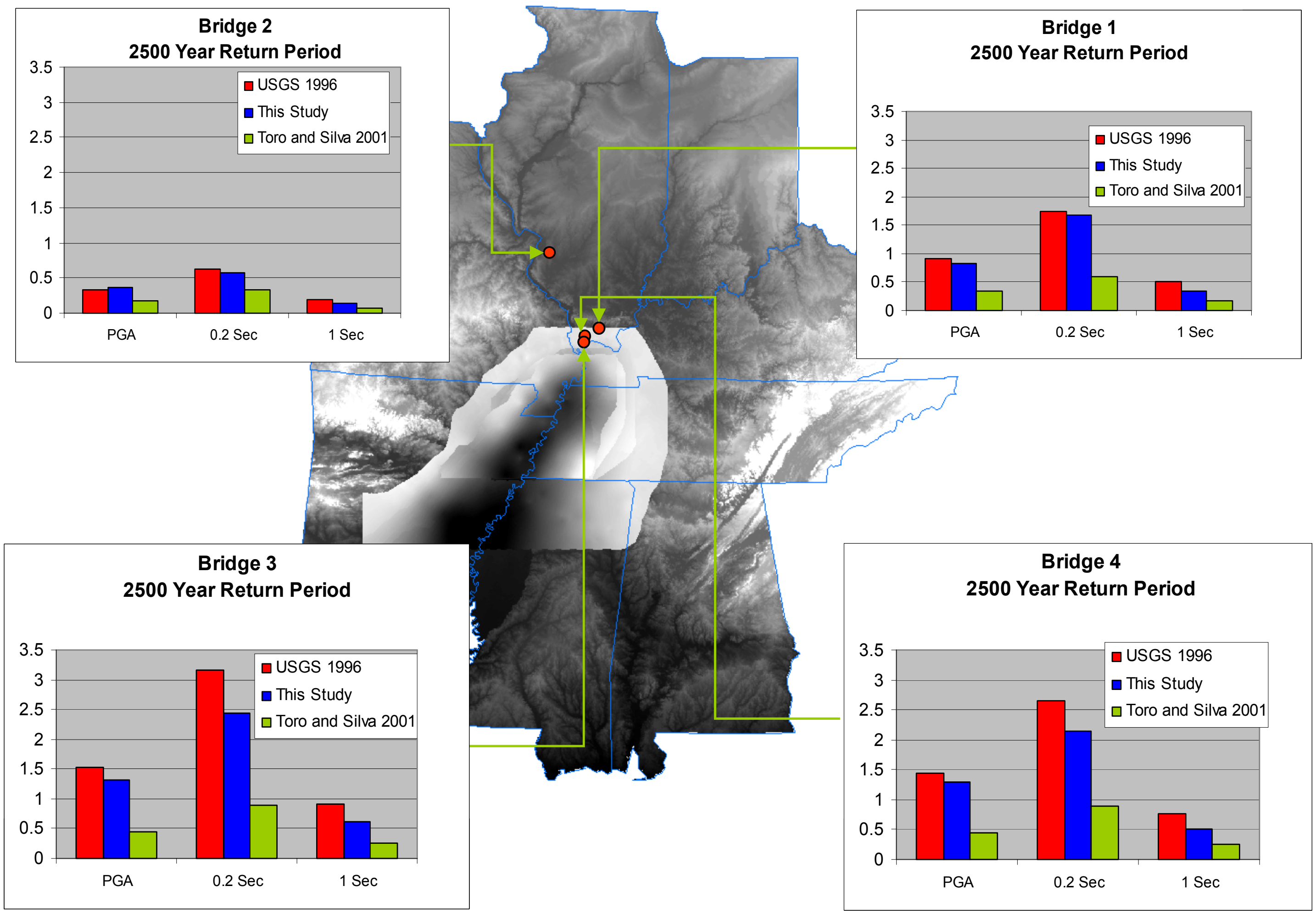


Figure 5. Locations of four bridge sites studied and the corresponding 0.2-second spectral accelerations and 1-second spectral acceleration, and PGA comparisons of three studies done by USGS 1996 hazard maps, Toro and Silva (2001) and this study at each site for a return period of 2500 years.

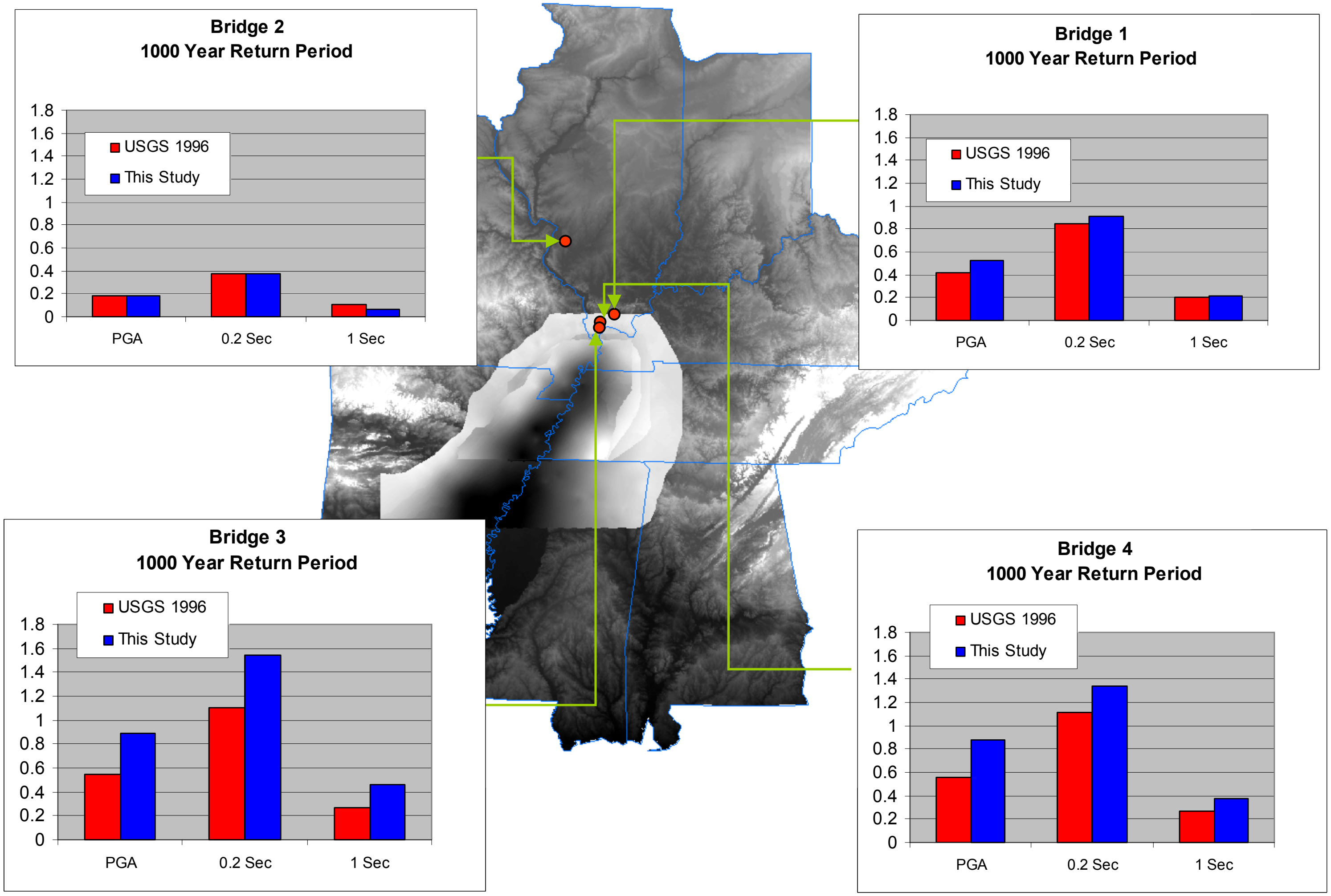


Figure 6. Locations of four bridge sites studied and the corresponding 0.2-second spectral accelerations and 1-second spectral acceleration, and PGA comparisons of three studies done by USGS 1996 hazard maps, Toro and Silva (2001) and this study at each site for a return period of 1000 years.

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