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Title: "A Proposal in Support of the St. Louis Area Earthquake Hazards Mapping Project: Update to Methodology and Urban Hazard Map Uncertainty Analysis"

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Summary

The St. Louis Area Earthquake Hazards Mapping Project (SLAEHMP) is a multi-year, multi-contributor project to develop seismic hazard maps for the greater St. Louis area that include the effects of local geology. Previously under NEHRP grant 08HQGR0016, a suite of central and eastern US (CEUS) specific hard-rock time-histories (seismograms) were developed and the seismic hazard model updated based on the 2008 version of the national seismic hazard model. In the first year of NEHRP grant G09AP00008 a more efficient hazard calculation methodology was implemented and applied to generating less detailed St. Louis regional probabilistic seismic hazard maps. Currently, hazard calculations with the effects of site geology are made by calculating both the hazard and the site amplification distribution every time a change is made in the soil model. In the first year of this grant I have implemented a methodology whereby the hard-rock hazard curves and site amplification distributions are calculated separately and combined probabilistically at the end. Both the new and old methodologies differ from the engineering practice of applying NEHRP soil factors to firm-rock ground motion estimates by being completely probabilistic and site-geology specific. Thus, with the new approach, hazard curves need to be calculated only once, as a standard hazard model is used. Changes and updates in site amplification distributions can then be made and applied to the existing hard-rock hazard curves, which offers a factor of 5 or more in computational savings. As part of this updating of the urban hazard mapping methodology, a more regional hazard assessment of the St. Louis area has been performed using regional reference profiles from the project (Karadeniz, 2007) and soil thickness values from Soller and Packard (1998). The reference profiles and soil thickness maps can be easily updated and applied as each more-detailed urban-hazard-mapping 7.5' quadrangle is completed. This will facilitate an improved general understanding of seismic hazard in the region in the short-term, and provide a quantitative means of documenting the improvements provided by the urban hazard maps over the regional maps in the long-term.

During the second year of this grant (G09AP00008) a full uncertainty analysis of the urban hazard map calculations was conducted. This goes beyond the sensitivity tests that have previously been done for the project to a full uncertainty assessment both in the hazard model and site amplifications used in the St. Louis project. Because the geology model is still being finalized, the uncertainty focus of this study is on the hazard model, although alternative ways of combining the hazard model and site amplification portions have been investigated. First the Monte Carlo computer programs were updated to use the 2008 USGS national hazard model and sample the logic trees associated with that model. Then an alternative method of combining the hazard model and site amplification into each realization of the Monte Carlo uncertainty analysis was developed, instead of handling each as a separate step and combining them at the end. Comparisons between these two approaches show small differences in the combined hazard mostly due to the Monte Carlo based site amplification distributions not being perfectly lognormal. Finally, for a single site, uncertainty analyses were run to show the relative contribution to the uncertainty in the 2008 USGS national hazard model results for St. Louis of the

New Madrid logic tree branches for attenuation model, rupture model, recurrence model, characteristic magnitude model, and seismogenic rupture length and width.

New Approach to PSHA calculation with the Effects of Local Geology

The site amplification and seismic hazard analysis procedures used in the St. Louis Area Earthquake Hazard Mapping Project (SLAEHMP) were developed under the Memphis urban hazard-mapping project (Cramer et al., 2004). These older procedures use a hazard calculation method that calculates both the hazard and the site amplification distribution every time a change is made in the soil model. In technical terms, the site amplification is applied inside the hazard integral over magnitude and distance to alter hard-rock ground motion attenuation relations to site-specific relations. The St. Louis project hopes to cover a fairly large area (29 or more quadrangles eventually) (Figure 1). Thus it would be more efficient to calculate the hard rock hazard curves once and then modify those curves with site amplification distributions as they are generated or improved. Such a procedure is available (Lee, 2000) and under this grant has been implemented for the St. Louis project.

St. Louis Area Earthquake Hazards Mapping Project

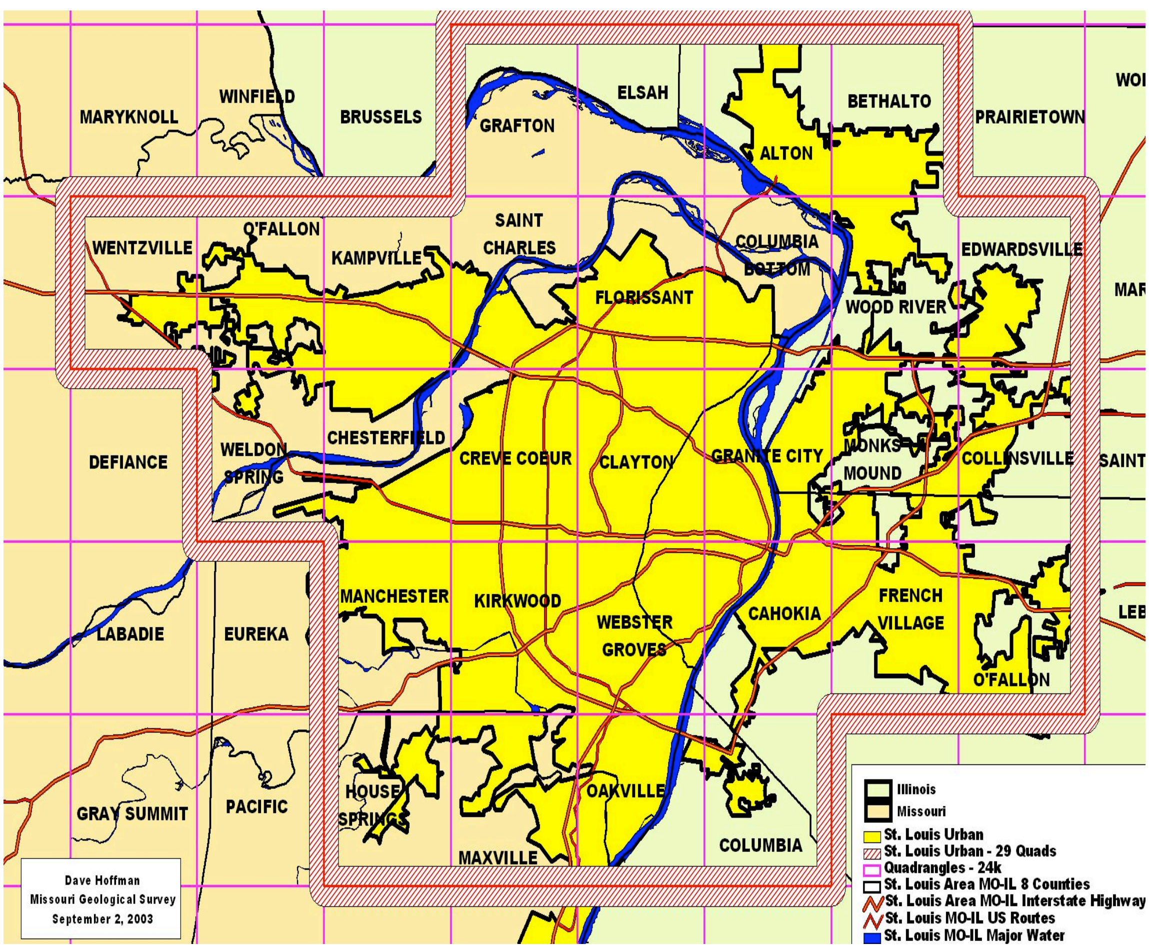

Figure 1: SLAEHMP study area.

Urban seismic hazard maps add in the effect of local geology on the amplification of earthquake ground motions in order to have more realistic ground motions for earthquake hazard analysis within the study area. To do this, information is needed about the local distribution and thicknesses of soil in the urban area. Basically, two sets of information are needed: what are the thicknesses at a site of each soil type (lithology) and what are each soil type's physical (geotechnical) properties that effect ground motion amplification. Site amplification at a site is determined by taking a soil profile (soil type, thicknesses, and physical properties) and subjecting that soil profile to earthquake shaking (time history) in the solid rock at the bottom of the soil profile to calculate the expected shaking at the surface of the ground. The change in amplitude of the shaking from the bottom to the top of the soil profile is site amplification.

Originally, the SLAEHMP probabilistic urban seismic hazard maps used the approach of Cramer (2003, 2005) to incorporate the effects of local geology (site amplification distributions) into the probabilistic seismic hazard calculations. This approach modifies hard-rock ground motion attenuation relations within the hazard integral.

For a given site, the probability, $P(A > Ao)$, of exceeding a specific ground motion Ao (Reiter, 1990, equation 10.2) is given by the seismic hazard integral

$$P(A > Ao) = \sum_I \alpha_I \int_M \int_R f_I(M)\, f_I(R)\, P(A>Ao \mid M,R)\, dR\, dM, \qquad (1)$$

where A is a ground-motion parameter (i.e., peak ground acceleration, PGA, or spectral acceleration, Sa), Ao is the ground motion level to be exceeded, α_I is the annual rate of occurrence of the ith source, M is moment magnitude, R is distance, $f_I(M)$ is the probability density distribution of earthquake magnitude of the ith source, and $f_I(R)$ is the probability density distribution of distance from the ith source. In the Cramer (2003, 2005) approach, hazard at a site (grid point) is calculated by applying the appropriate site amplification distribution $P(As \mid Ar)$, where As is soil ground motion and Ar is rock ground motion (both at the earth's surface), to the ground-motion attenuation relations within the hazard integral so as to alter them to site-specific attenuation relations. Thus, in equation 1, $A = As$ and $P(A>Ao \mid M,R)$ becomes $P(As>Ao \mid M,R)$ for a soil site, and

$$P(As>Ao \mid M,R) = 1 - \int_{Ar} P(As \leq Ao \mid Ar)\, P(Ar \mid M,R), \qquad (2)$$

where

$$P(As \leq Ao \mid Ar) = \int_{As:-\infty \to Ao} P(As = Ao \mid Ar)\, dA \qquad (3)$$

and

$$P(Ar \mid M,R) = d[1 - P(A > Ar \mid M,R)] / dA. \qquad (4)$$

Basically the site amplification distribution alters the rock hazard curve to a soil hazard curve for each earthquake in the hazard model before they are summed into the final soil hazard curve.

Lee (2000) has shown that instead of modifying the hazard curve of each earthquake in the hazard model and summing the resulting site-specific hazard curves to obtain the total site-specific hazard curve, the total hazard curve from the hard-rock hazard calculation can be modified directly by the site amplification distribution to make it site-specific:

$$P(As > Ao) = 1 - \int_{Ar} P(As \leq Ao \mid Ar)\, P(Ar), \qquad (5)$$

where $P(As \leq Ao \mid Ar)$ is given by equation 3, and $P(Ar)$ is from the total hard rock hazard curve and is given by

$$P(Ar) = d[1 - P(Ar > A)] / dA. \qquad (6)$$

This can be done because the site amplification distribution is explicitly independent of earthquake magnitude and distance and thus can be pulled outside of the seismic hazard integral (equation 1). It may seem that nonlinearity in soil response is implicitly dependent on magnitude and distance, but engineering models of nonlinear response are only dependent on the input level of ground motion. Further, the nature of the total hazard curve emphasizes that the strong ground motions come from the nearest, largest earthquakes and hence nonlinear soil behavior being a function of ground-shaking strength. Comparisons between these two approaches at the Savannah River Site indicate that both approaches yield essentially the same hazard result (Lee, 2006, personal communication) and this conclusion is confirmed by the application of the Lee (2000) approach to SLAEHMP under this grant (see below).

New Methodology Implementation

To implement the new approach, the same technique to modify a single earthquake's hazard curve (equation 2) was applied to the total hazard curve (equation 5). First the hard-rock total hazard curve for each site is calculated using the 2008 national seismic hazard codes (Petersen et al., 2008). Then the hard-rock total hazard curve at each site (grid point) is modified using equations 5 and 6 and that site's site amplification distribution in a manner much like that implemented by Cramer (2003, 2005) for individual earthquake hazard curves. Figure 2 compares the results from applying the old and new approaches compared with the original hard-rock hazard curve for a typical St. Louis site. The two approaches to incorporating the effects of local geology give very similar results, especially for probabilities of exceedance between 10^{-2} and 10^{-6}, which is typically sufficient for standard Probabilistc Seismic Hazard Analysis (PSHA) probabilities of exceedance. If more accuracy in the fit is desired for probabilities of exceedance less than 10^{-2}, additional ground motion levels can be added to the lower end of the hard-rock hazard curve and the site amplification distribution for the site.

The technique used to adjust the total hazard curve from hard-rock to a soil condition depends on the hazard curve being a complimentary cumulative probability distribution (ccpd). In fact, the total hazard curve is an annual rate of exceedance curve that must be converted to a ccpd by dividing by the zero ground motion annual rate of exceedance. The zero ground motion annual rate of exceedance must be estimated because it is normally not calculated by PSHA codes. For this application, I estimate the zero ground motion annual rate of exceedance value by projecting in lognormal space the slope of the lowest two ground motions available to the zero ground motion intercept. As can be seen in Figure 2, this estimation is less than perfect and causes a slight deviation from the more accurate within the hazard curve estimate over the first four to five points of the resulting hazard curve. If soil condition based hazard needs to be estimated at these lower ground motion levels from just the total hazard curve, then additional ground motion levels to well below the ground motion level of interest should be added to the lower end of the hard-rock hazard curve and the site amplification distribution for the site.

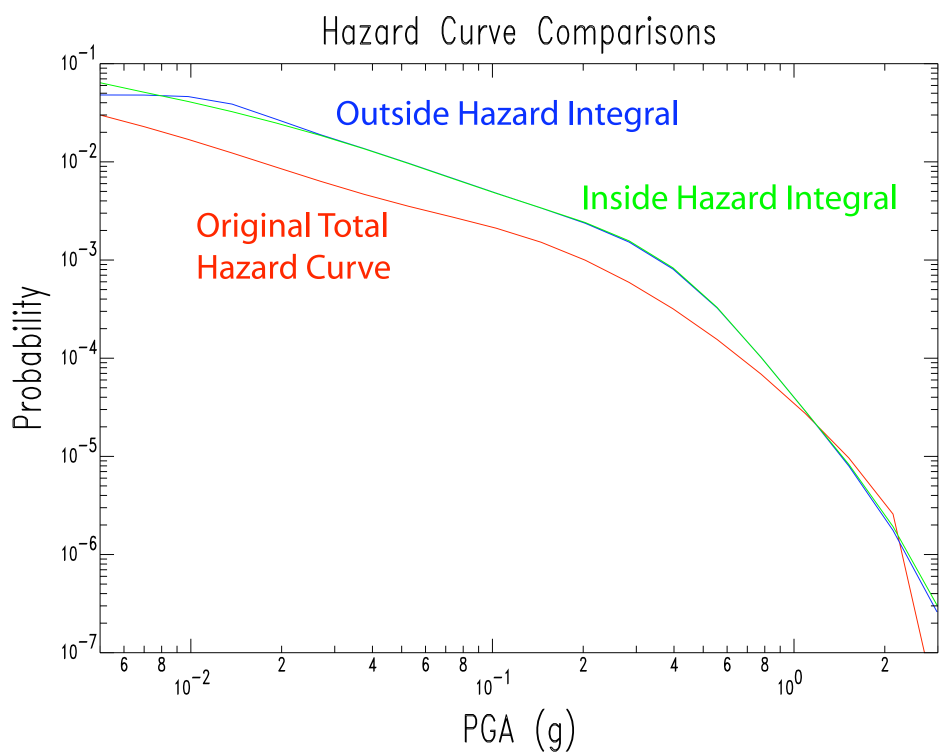

Figure 2: Comparison of hazard curves at a site in the St. Louis area showing the original hard-rock total hazard curve (red) and the resulting hazard curves with the effect of site geology using the inside the hazard integral approach (green – Cramer, 2003, 2005) and outside the hazard integral approach (blue – this report).

St. Louis Regional Probabilistic Ground Motion Maps

With the successful implementation of the outside the hazard integral approach to adding the effect of site geology, it can now be applied to generating St. Louis regional probabilistic ground motion maps with the effect of local geology. Cramer (2006) expanded the urban hazard mapping methodology to a more regional scale by using surface-geology-specific reference Vs profiles and available depth-to-bedrock information. To generate St. Louis regional maps we need to define a map grid, calculate hard-rock hazard curves for each point on the map grid, adopt appropriate Vs reference profiles, and select appropriate geology type and soil thickness regional information for the map grid.

A rectangular map grid covering the 29 quadrangles shown in Figure 1 was selected. A grid spacing of 0.01 degree (~1.0 km) was chosen to match the available regional geologic information (see below). The map grid extends from 38.37 N to 39.00 N in latitude and from 90.87 W to 98.88 W in longitude. This corresponds to 6400 grid points, more than six times the 988 grid points used in the Memphis urban hazard maps.

As for the most recent St. Louis urban hazard maps, the 2008 USGS national seismic hazard model is used to generate the regional hard-rock PSHA maps for this grid. Hard-rock PSHA maps were generated for peak ground acceleration (PGA), and 0.2 and 1.0 s spectral acceleration (Sa) for a 0.01 degree grid spacing.

Vs reference profiles and their uncertainty have been developed for SLAEHMP (Karadeniz, 2007). There are basically two profiles, one for lowlands alluvium and the other for uplands loess/till. Figure 3 presents these two profiles. These two profiles, with their uncertainty, have been used to generate appropriate site amplification distributions for use in making the regional PSHA maps (see below for details).

The needed regional geologic information about geology type and soil thickness has been taken from two sources: the CUSEC soil response map (Bob Bauer, June 2008, electronic communication) for geologic types produced with provinces defined by the Toro and Silva (2001) shear wave reference profiles for lowlands, uplands and glacial till, and Soller and Packard (1998) for soil thickness. The Soller and Packard regional soil thickness information has a grid resolution of 0.01 degree (~1.0 km), which governed the choice of grid spacing in generating the St. Louis regional probabilistic maps. The SLAEHMP urban hazard maps have a finer resolution of 0.005 degree (~0.05 km) and use more detailed geology and depth-to-bedrock information. The CUSEC geology type and Soller and Packard soil thickness information has previous been used to generate regional scenario ground motion maps for FEMA catastrophic planning purposes in 2008 (Cramer, 2009).

Figure 4 shows the geology type (uplands or lowlands) for the St. Louis region based on the CUSEC soil response map. The soils map contours have been sampled on the St. Louis regional map grid, assigning geology type (numeric values) depending on which geology type polygon the grid point fell within. A few values along the Mississippi River boundary between Missouri and Illinois had to be hand adjusted to lowlands due to boundary mismatches leaving the grid point outside both state boundary polygons.

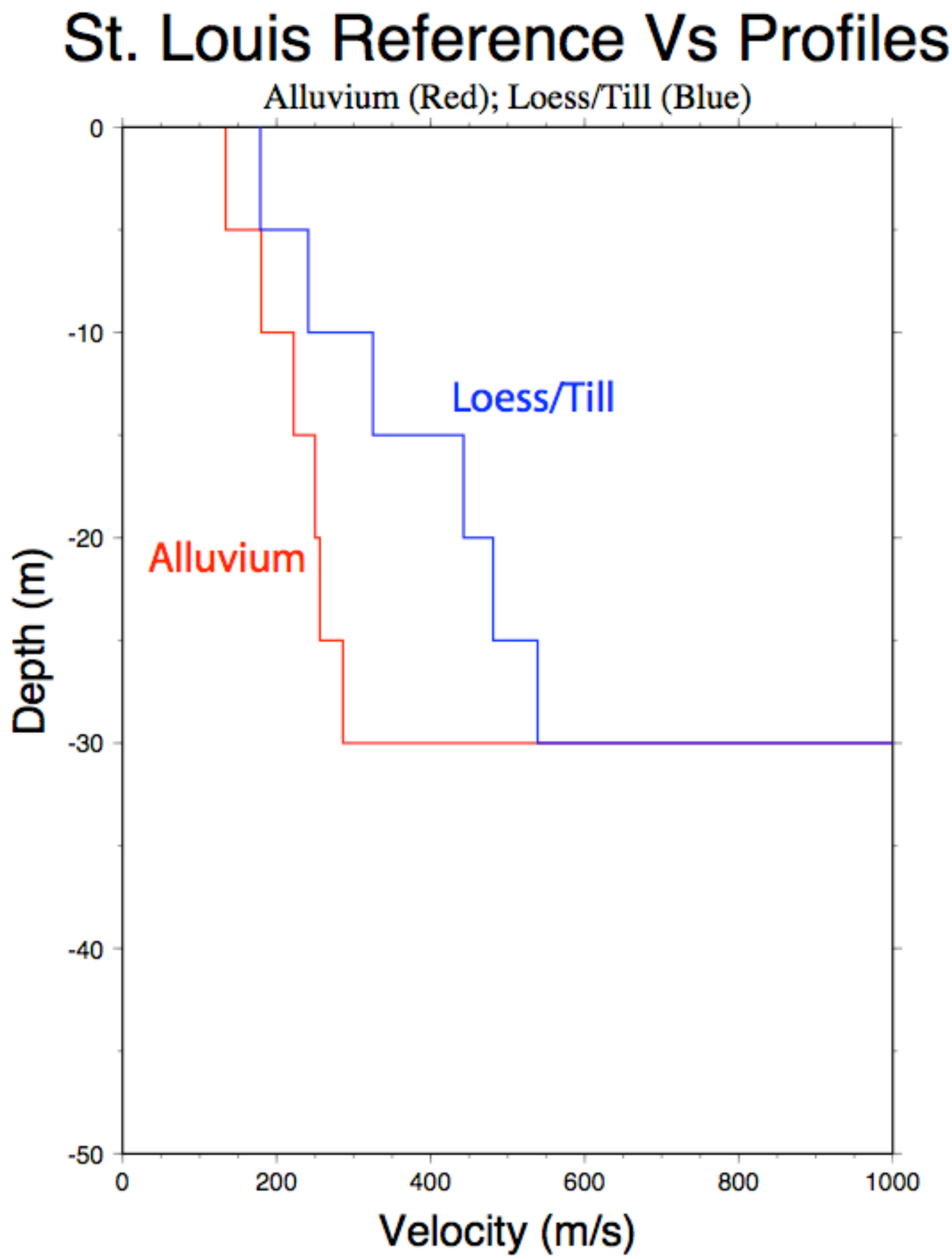

Figure 3: St. Louis Alluvial (lowlands) and Loess/Till (uplands) Vs reference profiles.

St. Louis Area Sediment Geology

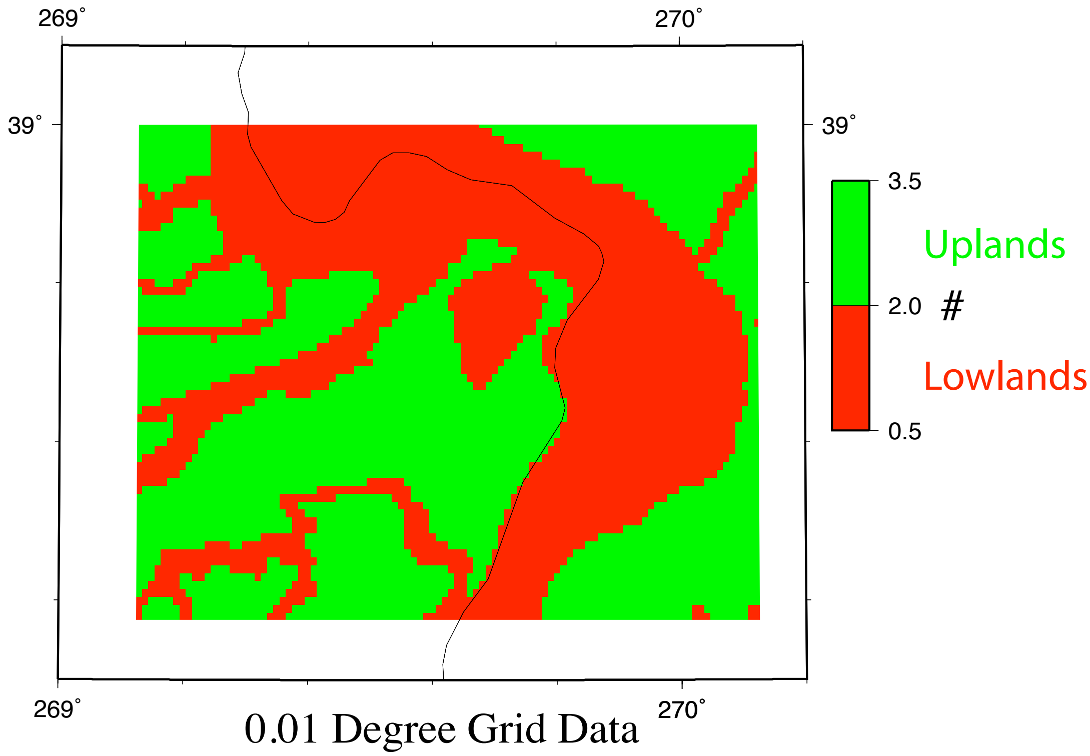

Figure 4: St. Louis general geology type from the CUSEC soil response map. The Mississippi river (state boundary) is shown as the black line traversing the Mississippi river flood plane (wide lowlands feature).

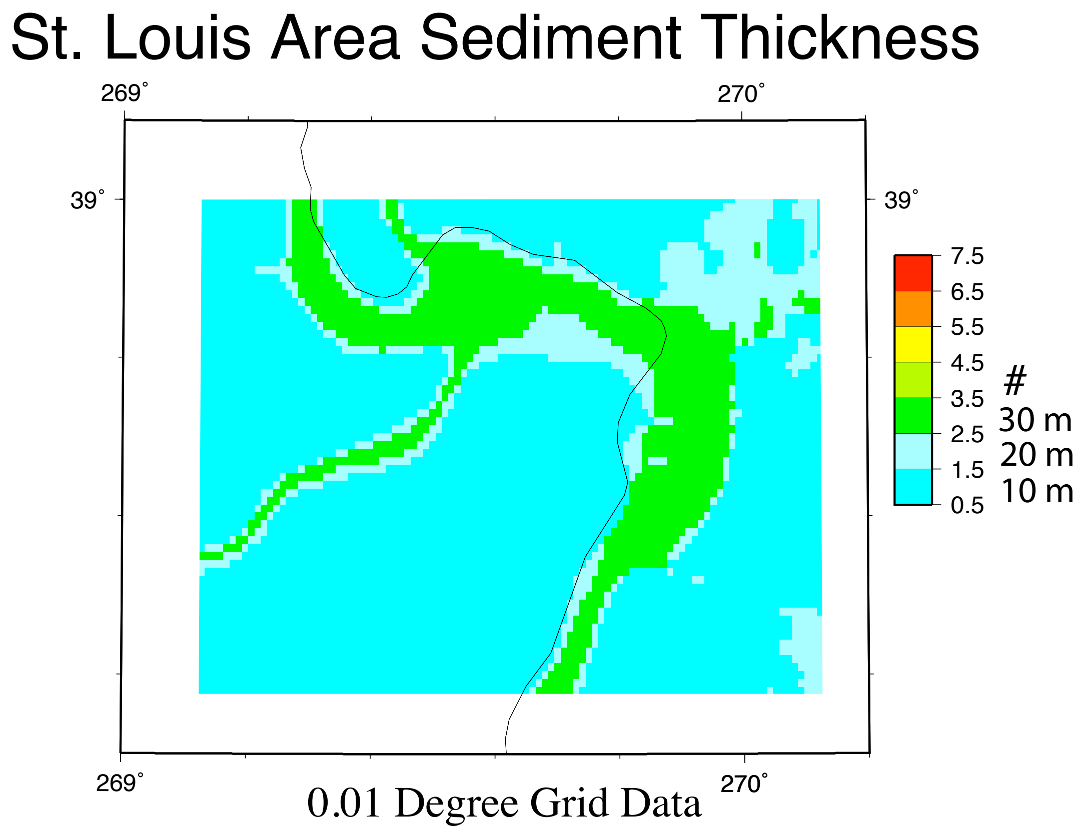

Figure 5: St. Louis region soil thickness from Soller and Packard (1998). The interpreted depth to bedrock for the three soil thickness ranges present in the map are indicated next to the thickness category scale. As in Figure 4, the Mississippi river (state boundary) is shown as a black line.

Figure 5 presents the St. Louis regional soil thickness information from Soller and Packard (1998). The Soller and Packard soil thickness information is discretized into soil thickness ranges. There are three depth ranges in the St. Louis region, and these have been interpreted to 10, 20, and 30 meter thick soils as indicated next to the scale bar in Figure 5.

Six sets of site amplification distributions (PGA, 0.2s Sa, and 1.0s Sa) for the St. Louis regional probabilistic maps were generated, one set for each general geology type (2) and soil thickness (3) bin. For each geology type and soil thickness value, the appropriate SLAEHMP Vs reference profile was selected and adjusted by placing the soil/rock boundary at the proper depth of 10, 20 or 30 m. Bedrock velocity was set at 2.8 km/s to match the hard-rock attenuation relations used in the USGS national seismic hazard model. The site amplification distribution is obtained from 100 Monte Carlo randomizations of the adjusted reference Vs profile, dynamic soil properties, and input time-histories as documented in Cramer (2006). The dynamic soil properties and input time-histories of M7 earthquakes (the dominate magnitude from the USGS national hazard model deaggregation for the St. Louis area) are the same as used for the Memphis urban hazard maps (Cramer et al., 2004) and upper Mississippi embayment regional hazard maps (Cramer, 2006). For the St. Louis regional probabilistic maps, the soil layer boundaries were held fixed due to the 5 m thick layers used in the SLAEHMP Vs reference profiles (Figure 3). To match the observed variance associated with each Vs reference profile, a standard deviation of 20% and 40%, respectively, were applied to the alluvial and loess/till Vs values during the Vs randomization process.

The generation of the St. Louis regional seismic hazard maps at each period (PGA, 0.2s, and 1.0s) of interest is accomplished by using the general geology type and soil thickness at each grid point to select the proper site amplification distribution for that grid point and then apply it to the hard-rock total hazard curve for that grid point using the new approach implemented by this grant to determine the effect of site geology on the hazard. The modified hazard curve for each period is saved to a file for that period along with its grid point coordinates. Specific hazard maps, such as 2%-in-50-year probability of exceedance, can then be generated from the saved modified hazard curves.

A test comparing computational speed between the older within the hazard integral method and the newer outside the hazard integral method was conducted to quantify computational savings by using the newer approach. A limited subset of regional grid points was used in calculations by both methods, once a file of site amplification distributions for each grid point was generated. Based on this test and previous experience from the Memphis urban hazard mapping calculations (~1000 grid points vs. over 6000 for St. Louis) and the computational time for the three St. Louis pilot urban hazard mapping quadrangles (~1900 grid points), the estimated computational time savings using the newer method for the St. Louis regional maps is a factor of 5 to 10, conservatively.

Figures 6-8 show the resulting PGA, 0.2s Sa, and 1.0s Sa St. Louis regional probabilistic hazard maps for 2%-in-50-year probability of exceedance. The New Madrid seismic zone to the southeast of St. Louis is the predominate source of hazard, as particularly shown in Figure 6. The PGA hazard map shows a low contrast (~0.05g) between the uplands and lowlands ground motion levels due to only a little more nonlinear soil behavior for the alluvium (lowlands), which is particularly evident in Figure 6b. For 0.2 s Sa the contrast between uplands and lowlands is stronger (~0.2 g) because the upland soils are stiffer and thinner than the lowland soils, in general. For 1.0 s Sa, the strong contrast (~0.1 g) between the uplands and lowlands is due to the thinness of the upland soils over bedrock (10 m or less) as indicated in Figure 5. Only the thicker soils in the river bottoms show strong 1.0 s amplification. This just emphasizes what has been observed elsewhere, that thicker alluvial soils tend to deamplify short period strong ground motions and significantly amplify long period strong ground motions.

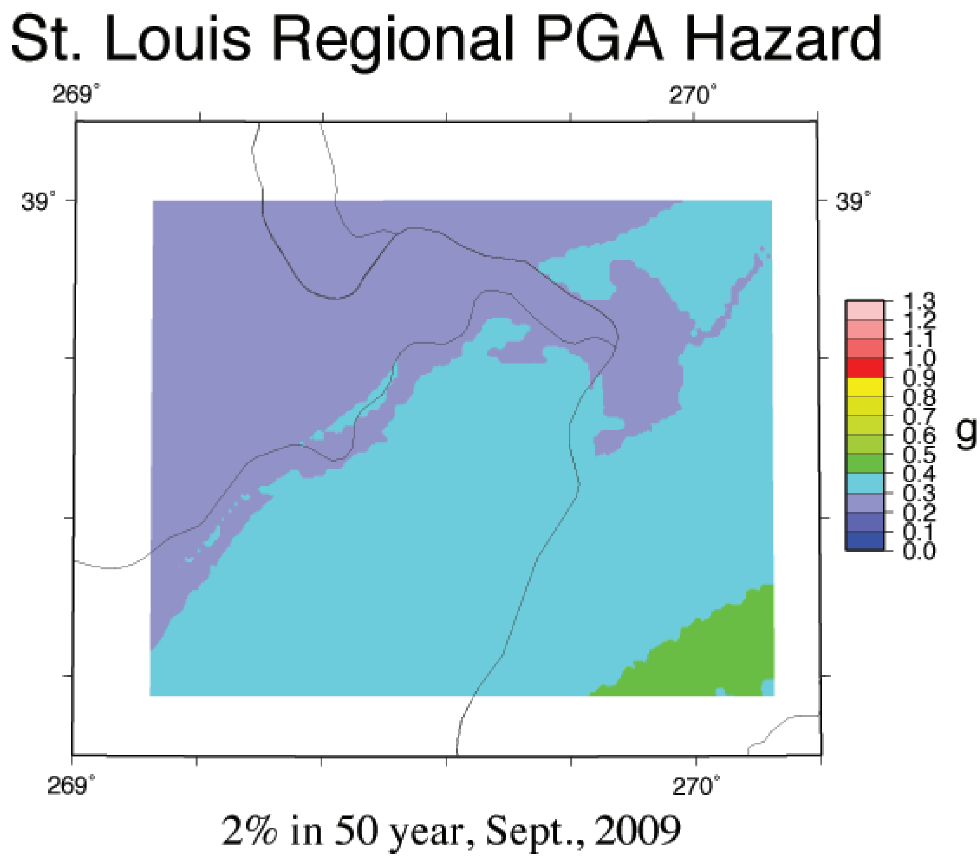

Figure 6a: St. Louis regional 2%-in-50-year PGA hazard map with a 0.1 g contour interval. Black lines show major rivers in the St. Louis area: Mississippi, Missouri, Illinois, and Kaskaskia (lower right corner outside hazard map).

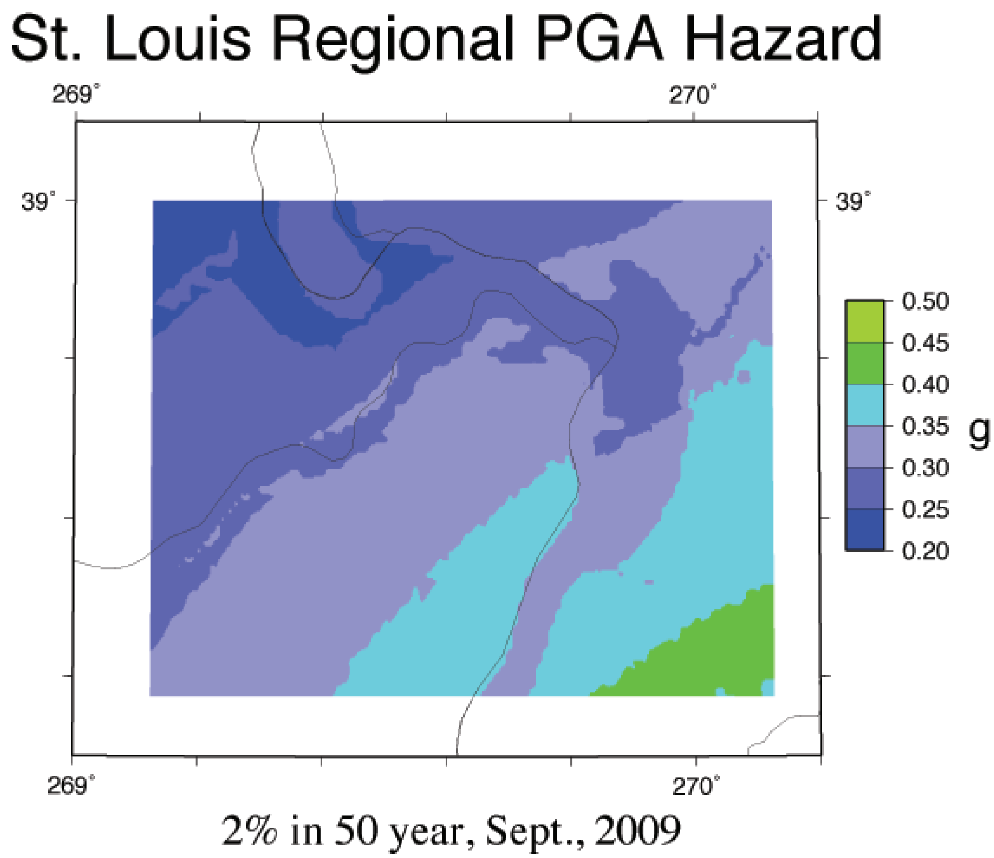

Figure 6b: Same map as in Figure 6a except with a 0.05 g contour interval instead of a 0.1 g contour interval.

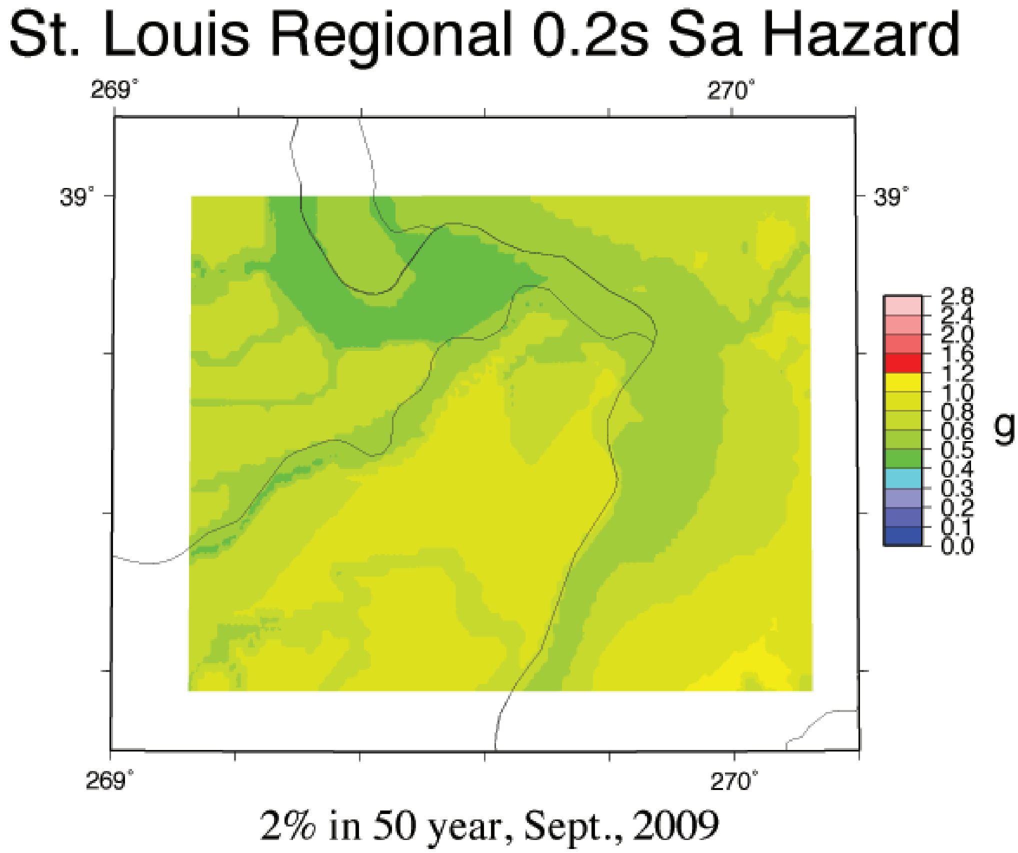

Figure 7: St. Louis regional 2%-in-50-year 0.2 s Sa hazard map with a 0.1 g (< 0.6 g) to 0.2 g (> 0.6 g) contour interval. Black lines show major rivers in the St. Louis area: Mississippi, Missouri, Illinois, and Kaskaskia (lower right corner outside hazard map).

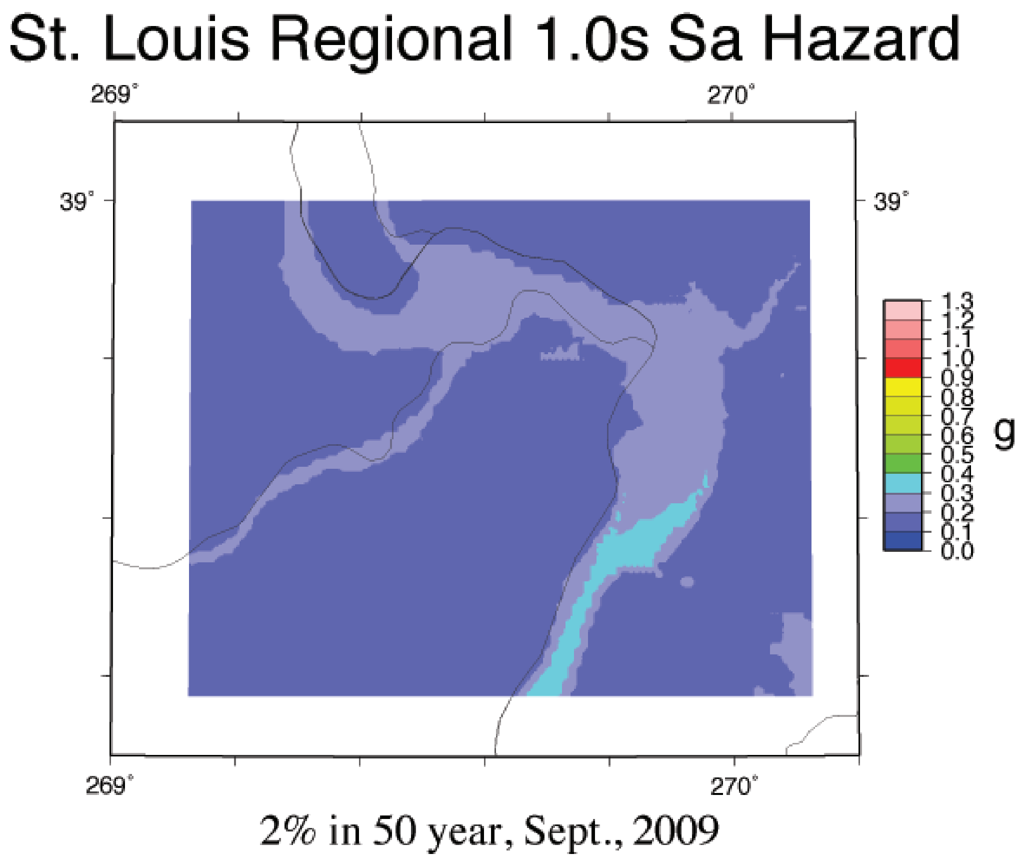

Figure 8: St. Louis regional 2%-in-50-year 1.0 s Sa hazard map with a 0.1 g contour interval. Black lines show major rivers in the St. Louis area: Mississippi, Missouri, Illinois, and Kaskaskia (lower right corner outside hazard map).

Comparison of Urban and Regional Hazard Maps

A comparison of the SLAEHMP three pilot quadrangle probabilistic urban seismic hazard maps (Cramer, 2009) inset into the St. Louis regional seismic hazard maps produced under this grant is shown in Figures 9-11 for PGA, 0.2 s Sa, and 1.0 s Sa, respectively. Basically, although not as detailed and based on less detailed information, the regional hazard maps show similar tends and levels of ground motion to the more detailed and higher resolution urban hazard maps. So far the urban seismic hazard maps show somewhat higher ground motions than the regional seismic hazard maps, possibly due to the greater geological detail and resolution incorporated into the urban maps. Nonetheless, these St. Louis regional seismic hazard maps will facilitate an improved general understanding of seismic hazard in the region in the short-term, and provide a quantitative means of documenting the improvements provided by the urban hazard maps over the regional maps in the long-term.

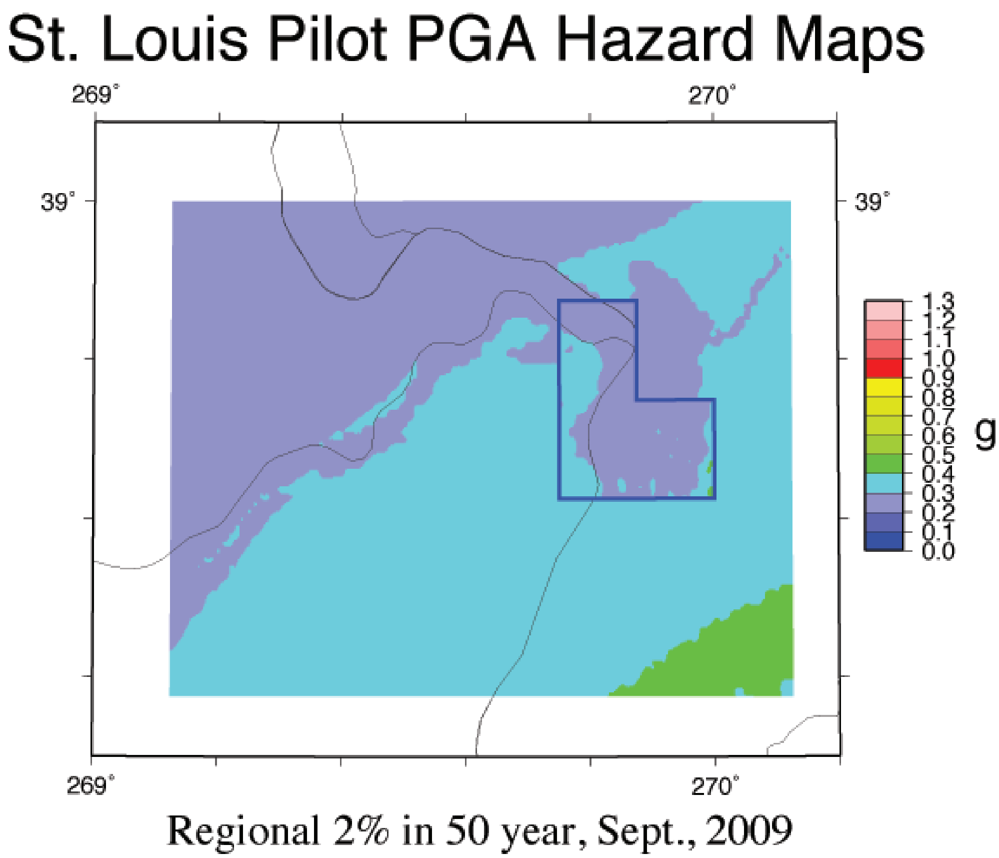

Figure 9: Detailed SLAEHMP three pilot quadrangle 2%-in-50-year PGA hazard maps (0.005 degree grid) inset into the less detailed and lower resolution (0.01 degree grid) St. Louis regional hazard map of Figure 6a.

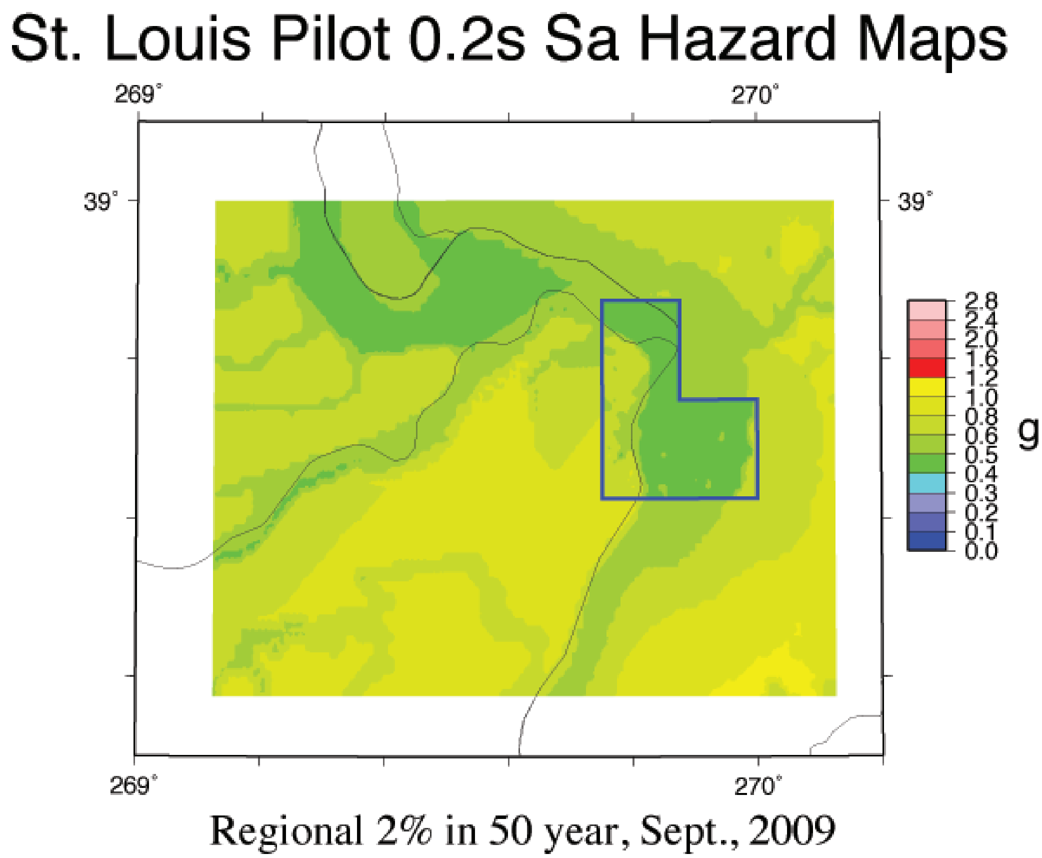

Figure 10: Detailed SLAEHMP three pilot quadrangle 2%-in-50-year 0.2 s Sa hazard maps (0.005 degree grid) inset into the less detailed and lower resolution (0.01 degree grid) St. Louis regional hazard map of Figure 7.

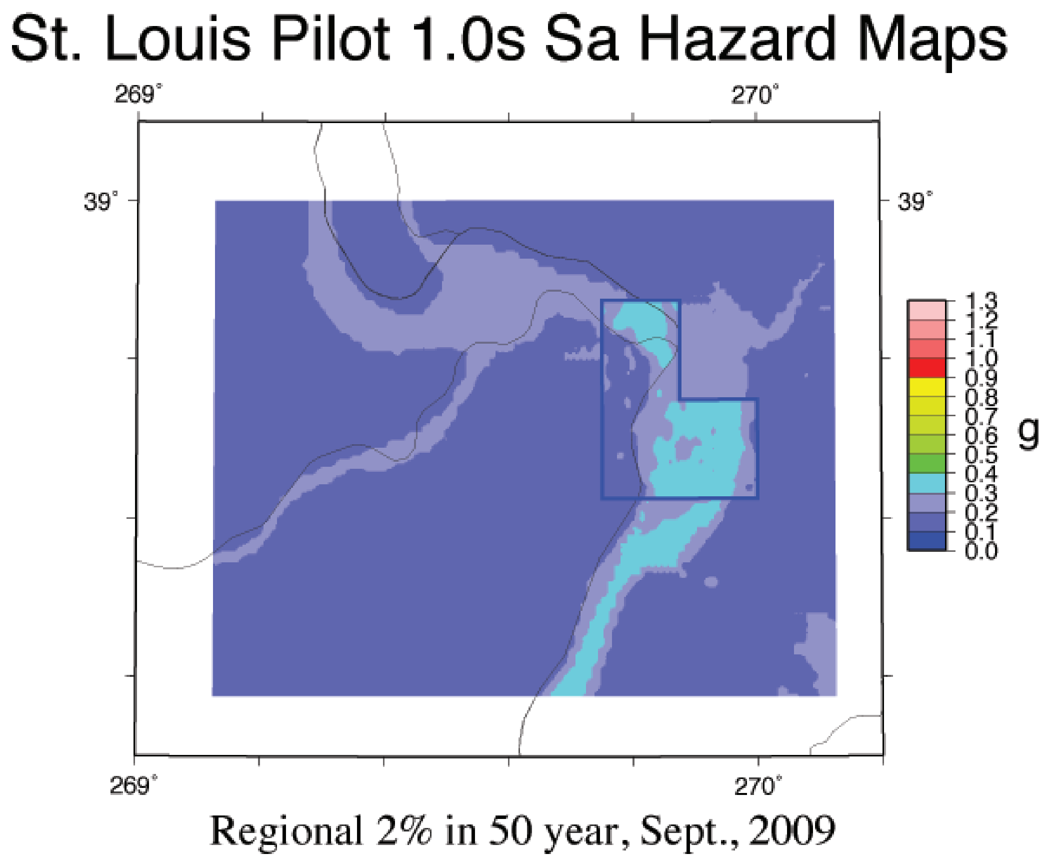

Figure 11: Detailed SLAEHMP three pilot quadrangle 2%-in-50-year 1.0 s Sa hazard maps (0.005 degree grid) inset into the less detailed and lower resolution (0.01 degree grid) St. Louis regional hazard map of Figure 8.

Uncertainty Analysis Approach

Sensitivity tests address the general sensitivity of a model to input parameters using generalized ranges that may not be specific to a particular analysis nor take known correlations among input parameters into account. An uncertainty analysis incorporates known parameter variability and correlations in determining which input parameters are more critical to a specific analysis. A complete uncertainty analysis of the St. Louis area seismic hazard model and site amplification distributions has been implemented. This analysis includes the 2008 update to the St. Louis area seismic hazard model and the change in hazard calculation procedure from the first year of this grant (see above). The uncertainty analysis uses the Monte Carlo approach of Cramer (2001), Cramer et al. (2002), and Cramer et al. (2004) whereby logic trees of model and parameter uncertainties are sampled using a Monte Carlo technique to form many realizations of the hazard model and site amplification. These realizations are then statistically analyzed for mean, median, fractile, variability, and coefficient of variation (standard deviation divided by the mean). Cramer et al. (1996) has shown that 100 realizations are sufficient for the Monte Carlo based analysis, but 200 realizations were used in this study in order to better sample low-probability logic-tree branches. The analysis includes the contribution to the uncertainty from individual parameters as well as the complete logic tree. This provides an evaluation of which parts of the model and input parameters contribute more to the overall uncertainty. Because of the changes in the national seismic hazard model in 2008, major changes were implemented in the above-cited uncertainty analysis computer codes in order to perform this task. The results of this uncertainty analysis are critical to understanding the strengths and weaknesses in the resulting urban hazard maps and to point out areas where future improvements can be made. Although the geologic model for the St. Louis area is not yet completed and uncertainty emphasis was placed on the hazard model portion of the uncertainty, the site amplification portion of the uncertainty analysis codes have been set up for use once the geologic model is finalized in 2011.

Separate vs. Combined Uncertainties

As part of the proposed uncertainty analysis, alternative ways of combining the hazard model and site amplification portions have been examined. The Memphis urban hazard map uncertainty analysis approach (Cramer et al., 2004) is to handle and calculate the hazard model and site amplification uncertainties separately. An alternative to this approach would be to combine both parts in the Monte Carlo uncertainty analysis by randomizing the hazard and site amplification models in each realization of the complete model, instead of a separate analysis. This latter approach should lead to higher overall uncertainties then the older Memphis urban hazard map approach. The alternative combined approach was implemented in the uncertainty analysis code and tests run at a single soil site both ways so as to better understand the overall uncertainty and the contributions of each part (hazard and site amplification) to the uncertainty.

Tables 1-3 list mean, median, and standard deviation (sd) results of the tests for peak ground acceleration (PGA) and for 0.2s and 1.0s spectral acceleration (Sa) for a probability of exceedance (PE) of 2% in 50 years. Although not shown, similar results were obtained for PEs of 5% and 10% in 50 years. The number of Monte Carlo runs (sampling of the logic trees) used was 20, 50, 100, 200, 500, and 1000 runs, as shown, in order to test the stability of differences in results between the two approaches. Clearly from Table 1, as expected, the overall sd of the PGA hazard estimates are lower for the separate uncertainties approach compared to the combined approach by a factor of about 2, except at 1.0s where there is only a 5% difference. Also, somewhat surprisingly, the mean and median values for the combined approach are somewhat but significantly less than the separate approach, although only by about 15% for PGA, 22% for 0.2s Sa, and 10% for 1.0s Sa.

Table 1: 2%-in-50y PGA (in units of g) at a St. Louis soil site (38.675N, 90.250W) for various numbers of runs and for both the separate and combined approach to including the effects of site geology.

	Separate:			Combined:		
# Runs	Mean	Median	StdDev	Mean	Median	StdDev
20	0.281	0.275	0.056	0.225	0.205	0.093
50	0.303	0.290	0.070	0.261	0.238	0.119
100	0.303	0.302	0.059	0.264	0.243	0.114
200	0.306	0.299	0.059	0.267	0.256	0.106
500	0.303	0.295	0.063	0.262	0.250	0.105
1000	0.300	0.291	0.062	0.260	0.248	0.100

Table 2: 2%-in-50y 0.2s Sa (in units of g) at a St. Louis soil site (38.675N, 90.250W) for various numbers of runs and for both the separate and combined approach to including the effects of site geology.

	Separate:			Combined:		
# Runs	Mean	Median	StdDev	Mean	Median	StdDev
20	0.438	0.423	0.064	0.348	0.322	0.140
50	0.489	0.461	0.099	0.376	0.238	0.148
100	0.495	0.495	0.085	0.383	0.243	0.169
200	0.513	0.510	0.089	0.404	0.256	0.187
500	0.514	0.505	0.091	0.402	0.250	0.176
1000	0.514	0.502	0.090	0.404	0.248	0.175

Table 3: 2%-in-50y 1.0s Sa (in units of g) at a St. Louis soil site (38.675N, 90.250W) for various numbers of runs and for both the separate and combined approach to including the effects of site geology.

	Separate:			Combined:		
# Runs	Mean	Median	StdDev	Mean	Median	StdDev
20	0.228	0.220	0.078	0.217	0.220	0.089
50	0.256	0.225	0.122	0.237	0.213	0.151
100	0.270	0.234	0.123	0.250	0.222	0.144
200	0.276	0.256	0.124	0.253	0.231	0.129
500	0.270	0.249	0.117	0.246	0.227	0.122
1000	0.276	0.257	0.116	0.249	0.231	0.118

Figures 12 – 14 show the mean, median, and sd of the PGA, 0.2s Sa, and 1.0s Sa site amplification distributions along with the actual site amplification realizations calculated for 20 Monte Carlo simulations. For the 0.1 - 0.2 g input ground motion range in Figure 12, the distribution of site amplification realizations (black lines) seems somewhat biased to the low side of the median curve, suggesting that the distribution of Monte Carlo realizations is not perfectly lognormal as assumed in applying the site amplification distributions (median and ln sd) to the hard rock hazard curves to obtain the site-specific soil hazard curves. This could provide the slightly lower hazard estimates for the combined approach seen in Table 1. Similar trends are seen in Figure 13 for 0.2s Sa that could explain the differences between separate and combined approach results in Table 2, while in Figure 14 in the input ground motion range below 0.1g there appears to have a slight upward bias in the individual realization that might lead to the combined approach having a slightly higher hazard than the separate approach. Table 3 shows much less of a difference between separate and combined approach results suggesting that the transitioning from a higher than median bias to a lower than median bias at 0.1g input motion in the 1.0s site amplification realizations has mostly neutralized the differences seen for PGA and 0.2s Sa.

Given that the site amplification realizations might be slightly skewed lower or higher from a true lognormal distribution, the use of the median and ln sd in calculating mean soil site hazard is justified and acceptable as the difference between the separate and combined approaches is less than 10-15% in ground motion hazard (except for the statistically inadequate 20 run examples in these three tables). This conclusion is more problematic for 0.2s site amplification distributions because the difference is a factor of 22%.

Also, Tables 1-3 show that the stability of the statistical estimates of mean hazard and uncertainty is not achieved until a minimum of 200 Monte Carlo samplings of the logic trees are used in the uncertainty analysis. Additionally, the uncertainty estimated from the separate hazard model and site amplification uncertainty calculation approach typically used in CEUS urban hazard mapping projects is generally low by a factor of 2, except for 1.0s Sa where it should be less than 5% higher. Thus the separate approach underestimates the uncertainty due to the site amplification component of the overall uncertainty.

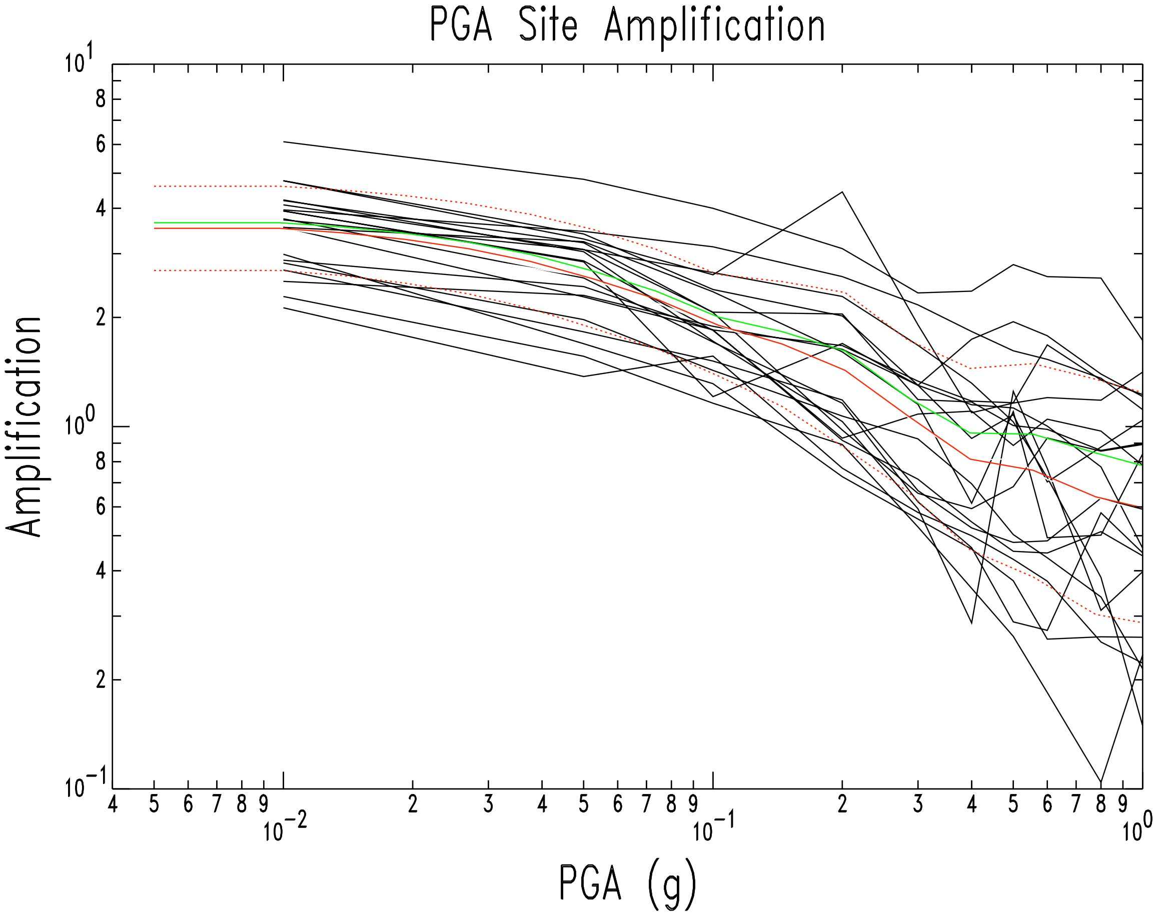

Figure 12: Site amplification curves for PGA for median (solid red), mean (solid green), plus and minus one sd (dotted red), and individual realizations (solid black).

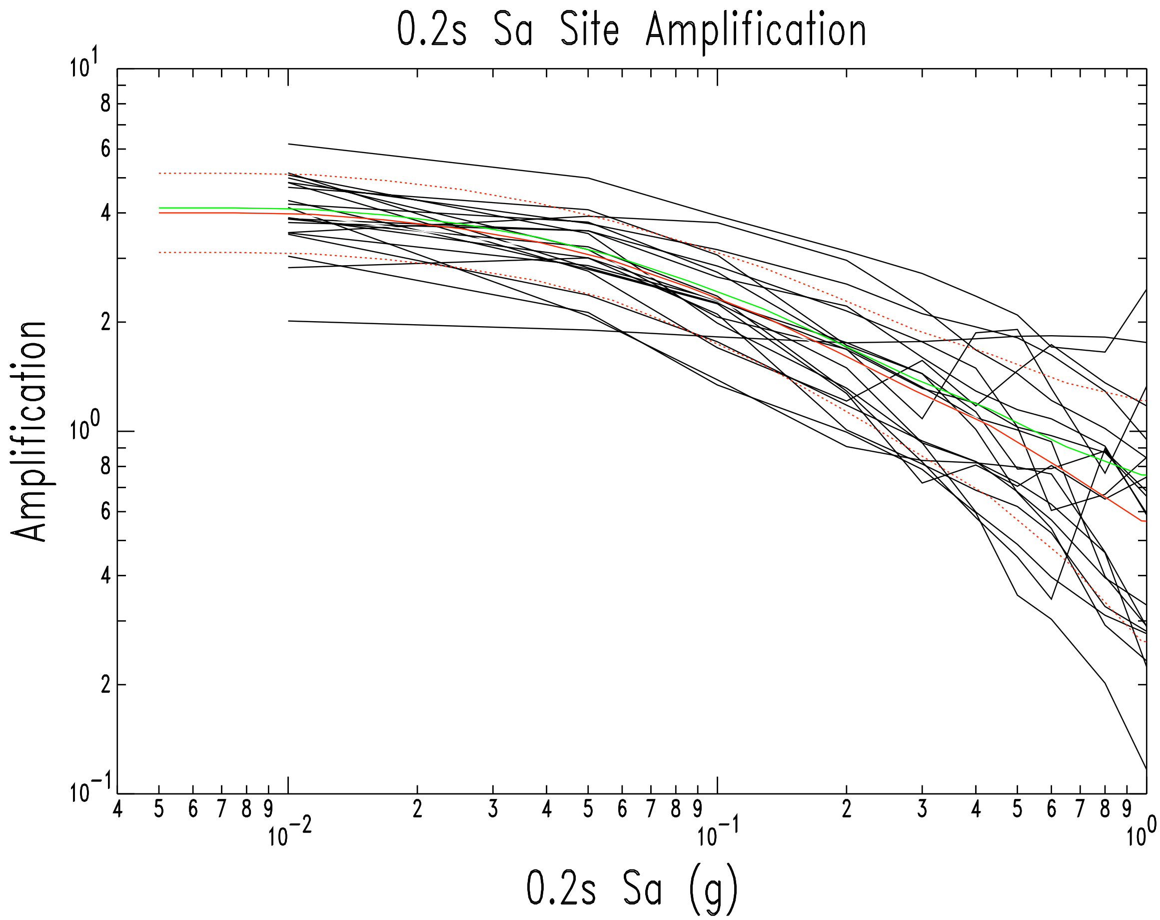

Figure 13: Same as Figure 12 for 0.2s Sa.

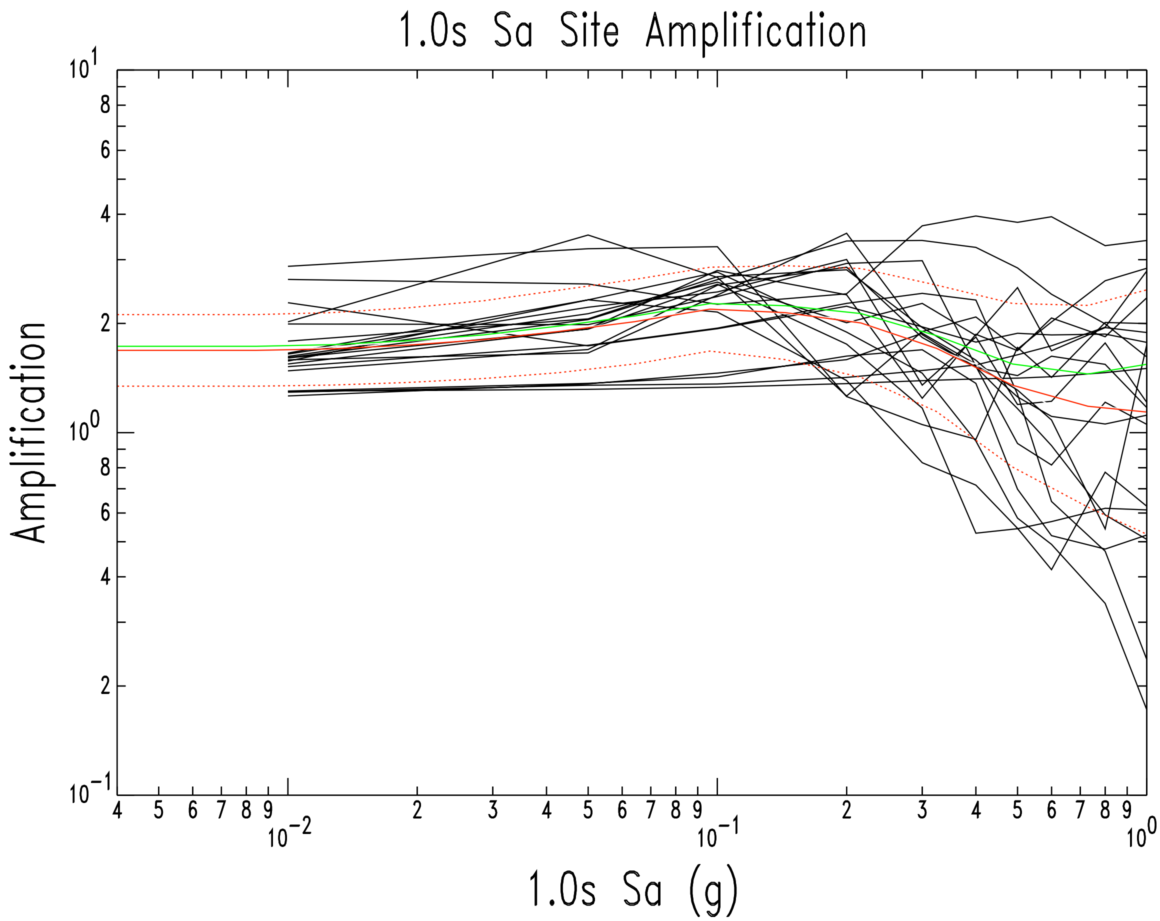

Figure 14: Same as Figure 12 for 1.0s Sa.

Contribution to Uncertainty

The New Madrid seismic zone (NMSZ) contribution to the uncertainty should dominate the overall uncertainty as shown in Cramer (2001). Cramer et al. (2002) shows that attenuation model uncertainty by far dominates the uncertainty due to the smoothed background model in the national seismic hazard maps. Additionally, Cramer (2001) indicates that the overall uncertainty and the New Madrid seismic zone contribution are not particularly spatially variable across the SLAEHMP study area. Thus, the examination of the overall contributors to uncertainty for St. Louis is limited to examining the trends at one soil site, as was done in the previous section, and to the attenuation, recurrence interval, characteristic magnitude, rupture location, rupture length, and rupture width branches in the logic tree of the national seismic hazard model.

Table 4 shows the overall and specific branch contributions to uncertainty for the St. Louis area, mainly from the NMSZ model. The coefficient of variation (CV) (sd/mean) is used as the measure of overall uncertainty and the contribution to uncertainty of one particular branch point. 200 Monte Carlo samplings of the logic trees were used in this analysis and the site amplification distribution applied using the separate approach of the previous section. Clearly, the CVs shown in Table 4 should be twice the values shown, except for 1.0 s Sa where they should be 5% higher, in order to properly consider the uncertainty due to the site amplification portion of the uncertainty.

From Table 4 we see that, other than site amplification, the attenuation model branch contributes the most to overall uncertainty in seismic hazard in the St. Louis area. This is followed by recurrence interval model, characteristic magnitude model, and rupture location model branches, in that order of level of contribution. The magnitude and rupture location branches have a similar level of contribution to the uncertainty. The rupture length and width models have little to no significant contribution to the overall uncertainty. For the Memphis, TN area, Cramer (2001) shows that the rupture location branch has a much more significant contribution to overall uncertainty because of the proximity of the NMSZ to Memphis. This is much less so for the St. Louis area as shown in Table 4.

Table 4: 2%-in-50y coefficients of variation (sd/mean) at a St. Louis soil site (38.675N, 90.250W) for a 200-run Monte Carlo sampling of the 2008 seismic hazard model logic trees at three periods (PGA, 0.2s, and 1.0s).

	PGA	0.2s Sa	1.0s Sa
All Branches	0.196	0.175	0.419
Attenuation Branch	0.154	0.113	0.282
Recurrence Interval Branch	0.056	0.065	0.115
Magnitude Branch	0.033	0.035	0.097
Rupture Location Branch	0.029	0.037	0.096
Rupture Length Branch	0.006	0.006	0.010
Rupture Width Branch	0.000	0.000	0.000

References

Cramer, C.H., 2001, A seismic hazard uncertainty analysis for the New Madrid seismic zone, *Eng. Geol.* **62**, 25-266.

Cramer, C.H., 2003, Site-specific seismic-hazard analysis that is completely probabilistic, *Bull. Seism. Soc. Am.* **93**, 1841-1846.

Cramer, C.H., 2005, Erratum: Site-specific seismic-hazard analysis that is completely probabilistic, *Bull. Seism. Soc. Am.* **95**, 2026.

Cramer, C.H., 2006, Quantifying the uncertainty in site amplification modeling and its effects on site-specific seismic-hazard estimation in the upper Mississippi embayment and adjacent areas, *Bull. Seism. Soc. Am.* **96**, 2008-2020.

Cramer, C.H., 2009, Final Technical Report, a proposal in support of the St. Louis Area Earthquake Hazards Mapping Project: suite of CEUS-specific hard-rock time-histories and seismic hazard model updates, USGS grand 08HQGR0016, February 20, 2009, CERI, 24 pp (available at http://earthquake.usgs.gov/research/external/reports/08HQGR0016.pdf).

Cramer, C.H., M.D. Petersen, and M.S. Reichle, 1996, A Monte Carlo approach to estimating uncertainty for a seismic hazard assessment of Los Angeles, Ventura, and Orange counties, California, *Bull. Seism. Soc. Am.* **86**, 1681-1691.

Cramer, C.H., R.L. Wheeler, and C.S. Mueller, 2002, Uncertainty analysis for seismic hazard in the southern Illinois basin, *Seism. Res. Lett.* **73**, 792-805.

Cramer, C.H., J.S. Gomberg, E.S. Scheig, B. A. Waldron, and K. Tucker, 2004, *Memphis, Shelby County, Tennessee, seismic hazard maps*, U.S. Geological Survey, Open-File Report 04-1294, 41pp.

Karadeniz, D. (2007). *Pilot program to assess seismic hazards of the Granite City, Monks Mound, and Columbia Bottom quadrangles, St. Louis metropolitan area, Missouri and Illinois*, Ph.D. Thesis, University of Missouri – Rolla, 290 pp.

Lee, R.C., 2000, A methodology to integrate site response into probabilistic seismic hazard analysis, Site Geotechnical Services, Savannah River Site, report of 3 February 2000.

Petersen, M.D., A.D. Frankel, S.C. Harmsen, C.S. Mueller, K.M. Haller, R.L. Wheeler, R.L. Wesson, Y. Zeng, O.S. Boyd, D.M. Perkeins, N. Luco, E.H. Field, C.J. Wills, and K.S. Rukstales (2008). *Documentation for the 2008 Update of the United States national seismic hazard maps*, U.S. Geological Survey, Open-File Report 2008-1128 (http://pubs.usgs.gov/of/2008/1128/ OF08-1128_v1.1.pdf).

Reiter, L., 1990, *Earthquake Hazard Analysis: Issues and Insights*, Columbia University Press, New York.

Soller, D.R. and P.H. Packard (1998). Digital representation of a map showing the thickness and character of quaternary sediments in the glaciated United States east of the Rocky Mountains, U.S. Geol. Surv. Digital Data Series DDS#38.

Toro, G.R., and Silva, W.J., 2001, Scenario earthquakes for Saint Louis, MO, and Memphis, TN, and seismic hazard maps for the central United States region including the effect of site conditions, Final technical report to the USGS for grant 1434-HQ-GR-02981, 10 January 2001, Risk Engineering, Inc., Boulder, Colorado, 248 pp.

Publications from this Research

No publications have resulted from this research as of this date. Future papers based on this work will be provided, as required, when publication occurs.