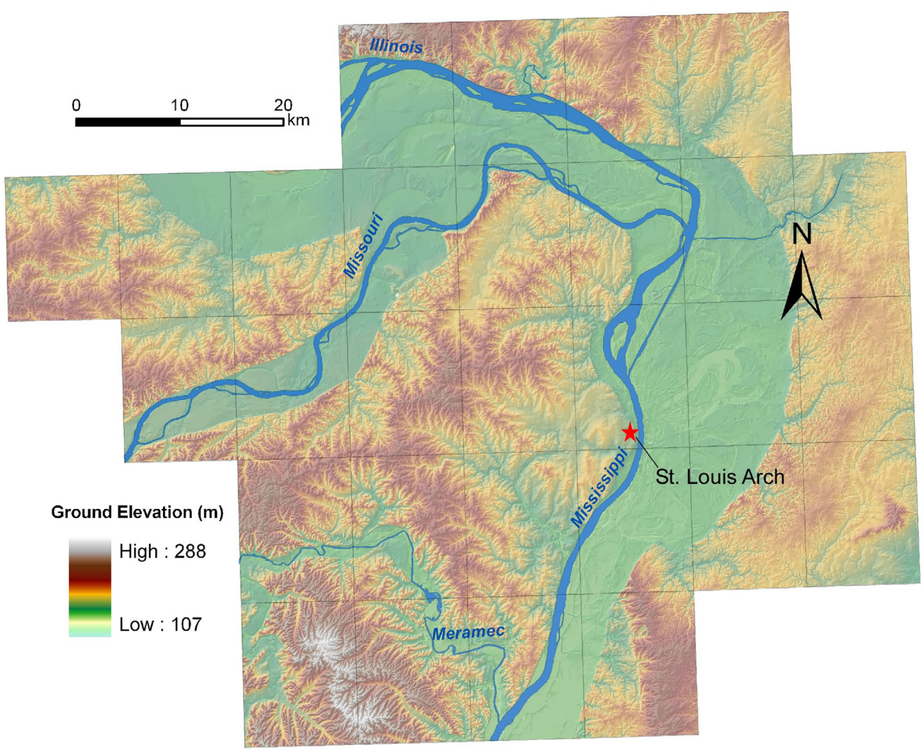
St. Louis Area Earthquake Hazards Mapping Project—A Progress Report-November 2008

By D. Karadeniz, J.D. Rogers, R.A. Williams, C.H. Cramer, R.A. Bauer, D. Hoffman, J. Chung, G.L. Hempen, P.J. Steckel, O.L. Boyd, C.M. Watkins, N.S. McCallister, and E. Schweig

In collaboration with the St. Louis Area Earthquake Hazards Mapping Project (SLAEHMP)



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Cover: St. Louis metropolitan area encompasses 29 USGS quadrangles shown on shaded relief map.

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Executive Summary

St. Louis has experienced minor earthquake damage at least 12 times in the past 200 years. Because of this history and its proximity to known active earthquake zones, the St. Louis Area Earthquake Hazards Mapping Project (SLAEHMP) is producing digital maps that show variability of earthquake hazards, including liquefaction and ground shaking, in the St. Louis area. The maps will be available free via the internet. Although not site specific enough to indicate the hazard at a house-by-house resolution, they can be customized by the user to show specific areas of interest, such as neighborhoods or transportation routes.

Earthquakes currently cannot be predicted, but scientists can estimate how strongly the ground is likely to shake as the result of an earthquake. Earthquake hazard maps provide one way of conveying such estimates. The U.S. Geological Survey (USGS), which produces earthquake hazard maps for the Nation, is working with local partners to develop detailed maps for urban areas vulnerable to strong ground shaking. These partners, which along with the USGS comprise the SLAEHMP, include the Missouri University of Science and Technology-Rolla (Missouri S&T), Missouri Department of Natural Resources (MDNR), Illinois State Geological Survey (ISGS), Saint Louis University, Missouri State Emergency Management Agency, and URS Corporation. Preliminary hazard maps covering a test portion of the 29-quadrangle St. Louis study area have been produced and are currently being evaluated by the SLAEHMP. A USGS Fact Sheet summarizing this project was produced and almost 1000 copies have been distributed at several public outreach meetings and field trips that have featured the SLAEHMP (Williams and others, 2007). In addition, a USGS website focusing on the SLAEHMP, which provides links to project results and relevant earthquake hazard information, can be found at: http://earthquake.usgs.gov/regional/ceus/urban_map/st_louis/index.php. This progress report summarizes the methodology and data used to generate these preliminary maps. For more details about many of the topics in this summary the reader is referred to the Karadeniz (2007) and Chung (2007) Ph.D. theses.

Abstract

Draft probabilistic and deterministic seismic hazard maps for the St. Louis metropolitan area, which include the effects of surficial geology on site response, have been prepared for three pilot USGS 7.5-minute quadrangles of the 29-quadrangle study area. The computer codes used in this study, which are similar to those used in the generation of the USGS national seismic hazard maps (Frankel, 2002), were modified for use in this study by Cramer (2003). These codes, which were implemented by Karadeniz (2007) in his Ph.D. thesis on St. Louis area seismic hazards, account for the fully-probabilistic approach in developing the maps and apply the median of site amplification estimates to the hard-rock ground motion attenuation relations in the deterministic maps. All of the seismic hazards were calculated based on a grid of 0.005°, or about every 500 m, the same spacing employed in the amplification distribution calculations. To account for some of the uncertainty found in St. Louis area shear-wave velocity measurements, shear modulus proxies, depth to bedrock calculations, earthquake time histories, and so on, a Monte Carlo randomization procedure was used to generate site-amplification distributions and provide an estimate of the uncertainty, in terms of mean, median, and standard deviation. These distributions were assumed to be lognormal in form.

In this study one-dimensional equivalent-linear response analysis was used to evaluate site-amplifications because of the following reasons: 1) high strain levels are not expected; 2) high excess water pressure development is not expected, and 3) the bedrock structure and overlying soft-sediment layering is near-horizontal in the St. Louis area. When compared to the USGS National Maps, the new probabilistic hazard levels calculated in the pilot study area for upland sites (loess covered residuum, drift, till) show zero to 300 percent greater ground motion levels for peak ground acceleration (PGA), 200 to 250 percent greater ground motion levels for 0.2-s spectral acceleration (SA), and 0 to 175 percent greater ground motion levels for 1.0-s SA. Probabilistic hazard levels for lowland (alluvial) sites, generally the modern Mississippi and Missouri River floodplains, exhibit zero to 200 percent greater ground motion levels for PGA, between 20 percent smaller to 150 percent greater ground motion levels for 0.2-s SA, and 100 to 260 percent greater ground motion levels for 1.0-s SA, when compared to the National Hazard Map.

A complimentary project in the St. Louis area by William Lettis & Associates (funded by the National Earthquake Hazard Reduction Program—NEHRP) has been the generation of liquefaction hazard maps in 12 USGS 7.5-minute quadrangles of the St. Louis metropolitan area (Pearce and Baldwin; 2008). Their study assesses the relative susceptibility of Quaternary geologic deposits to earthquake-induced liquefaction. Based on this analysis they constructed 12 GIS-based, 1:24,000-scale, liquefaction susceptibility maps. Their work differentiated four primary geologic units: artificial fill, Holocene alluvium, Pleistocene glacio-fluvial outwash, and Pleistocene loess. The results of the integrated analysis show that Holocene alluvial units in the lowlands and in a few stream valleys of the uplands are the most susceptible to liquefaction. Late Pleistocene glacio-fluvial outwash has a moderate-to-low susceptibility; the loess deposits in the uplands have a very low susceptibility. Artificial-fill deposits are common, and are assigned a conservative value of "very high" liquefaction susceptibility because of the difficulties associated with estimating their geotechnical properties, and thus the ability to forecast their response to seismic shaking. Since many transportation routes, power and gas transmission lines, and population centers exist in or on the highly susceptible Holocene alluvium, the St. Louis region is at significant potential risk from seismically induced liquefaction and liquefaction-related ground deformation.

Introduction

The SLAEHMP is a key part of the USGS Earthquake Hazards Program, which seeks to reduce the Nation's risk from earthquake hazards; other metropolitan areas that are a part of this national program include Seattle, Wash., Evansville, Ind., Memphis, Tenn., Reno, Nev., and the Wasatch Front, Utah urban corridor. The project addresses earthquake hazards throughout the St. Louis metropolitan area, a densely populated urban zone, which is split between Missouri and Illinois (fig. 1). The region has experienced strong ground shaking as a result of pre-historic and contemporary seismicity associated with the major neighboring seismic source areas, including the Wabash Valley Seismic Zone (WVSZ) and New Madrid Seismic Zone (NMSZ) (fig. 1). The goal of the St. Louis project is to produce practical hazards maps and an internet-accessible database that can be used by those in the geosciences, design communities, and city and county planning agencies and would allow these groups to more accurately plan for events of this nature.

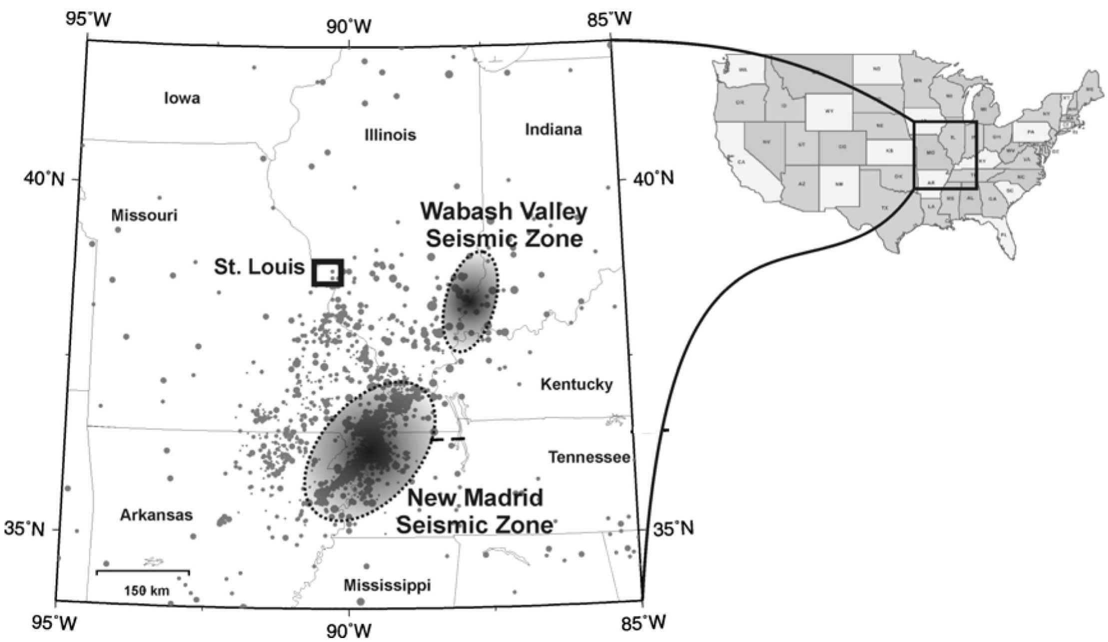

Figure 1. Seismicity of Midwestern United States and the areal extent of the New Madrid and Wabash Valley Seismic Zones relative to the St. Louis area. Dots represent the seismic activity recorded during historic time. The diameters of the circles represent earthquake epicenters, with increasing magnitude.

In response to earthquake hazard potential in other parts of the Midwest, in 2004 the USGS Memphis office organized the SLAEHMP. The project is guided by a Technical Working Group (TWG) consisting of earth scientists and engineers from local firms, universities, and government agencies. The TWG convenes four times a year to discuss mutual goals and assignments focusing on evaluating relative seismic risks and ground shaking hazards posed to the St. Louis Metropolitan area.

The study area encompasses about 4,000 square km across 29 USGS 7.5-minute quadrangles (fig. 2). The objectives of this project are to: 1) create detailed maps of earthquake hazards in the St Louis area,

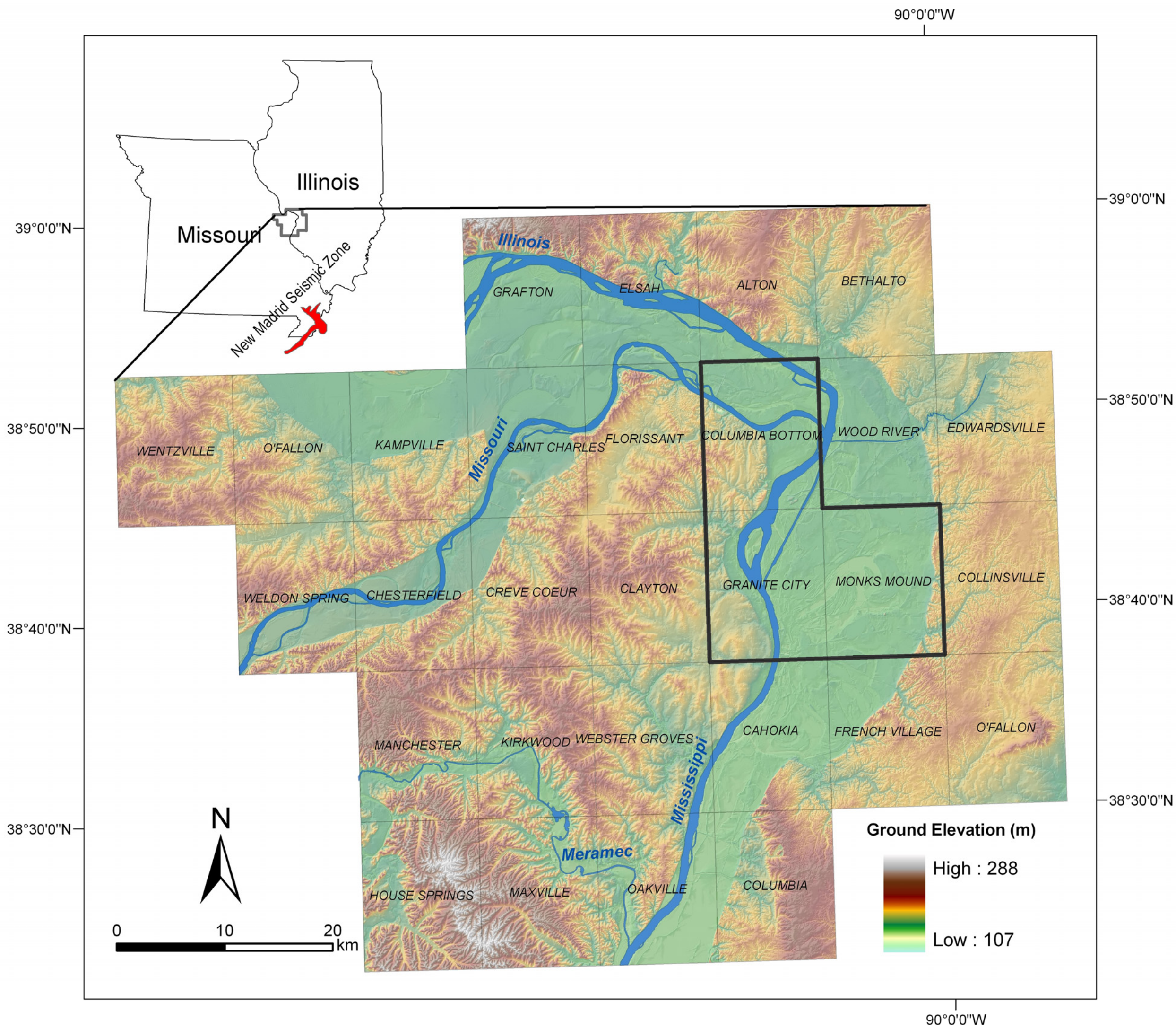

Figure 2. The St. Louis metropolitan area encompasses 29 USGS quadrangles as shown on this shaded relief map. The three pilot quadrangles highlighted in this report (Monks Mound, Granite City, and Columbia Bottom) are outlined (heavy black line). The general outline of NMSZ seismicity is shown as the red area in the upper left (after Hoffman 2005, personal commun.; Chung, 2007).

2) create a three-dimensional database of geologic and geotechnical information (largely completed although ongoing and focusing on sparse data areas), and 3) enlist practical input from stakeholder and end users of the hazard maps. A principal short-term goal, which is largely accomplished and being evaluated by the TWG, is to produce earthquake hazard maps for three pilot quadrangles (Granite City, Monks Mound, and Columbia Bottom) that will allow assessment of the

methodology before proceeding to the remaining 26 quadrangles in the study area. The array of hazard maps and their format will be very similar to the format established by the USGS for the Memphis/Shelby County Seismic Hazard Mapping project completed in 2004. Detailed surficial geologic mapping of the entire study area will probably be completed over the next 3-4 years, but a complete set of hazard maps for a larger subset of the 29-quadrangle study area adjoining the three pilot quads should be completed in about 2 years.

This region is, for the most part, located on unconsolidated Quaternary deposits which consists of: 1) lowlands of alluvial deposits in floodplains along four major rivers (Mississippi, Missouri, Illinois, and Meramec), and 2) uplands of loess over residuum or over glacial till or drift deposits (Goodfield, 1965; Grimley and others, 2007; Grimley and Phillips, 2006). Bedrock shallowly underlies the Quaternary deposits in the St Louis region and largely consists of flat-lying sedimentary rock formations, mostly Mississippian-age limestone and Pennsylvanian-age shale (Harrison, 1997). According to borehole data provided by the Missouri and Illinois Geological Surveys, the depths to bedrock are generally about 30 to 40 m and about 0 to 15 m in lowlands and uplands, respectively.

Methodology

The physical properties of the bedrock and Quaternary deposits in the St. Louis area will strongly influence seismic wave transmission through the region. It is well known that the bedrock of the Central and Eastern United States (CEUS) is older and more indurated than that in the western United States, such as California, and partly as a result of this, seismic energy is transmitted much more efficiently in the CEUS. These properties of CEUS bedrock also lead to higher seismic wave speeds, less energy attenuation, and permit crustal earthquake waves to spread laterally over much larger areas (Nuttli, 1973).

The site response analyses used in this study considered the time-histories at the base of the Quaternary deposits and assume a flat (horizontal) boundary between the Quaternary and the underlying bedrock. In the St. Louis study area, the Quaternary-rock interface is nearly horizontal, so focusing effects are not expected to be a strong influence. Past experiences have demonstrated that the intensity of ground shaking may vary considerably during any given earthquake, depending on the underlying geology. Our seismic hazard analyses depend on ground shaking estimates which, in turn, are based on accurate subsurface characterization of the geology. Some fundamental uncertainties always exist, however, with the accuracy of the subsurface models, which are estimates based on data from borings or other subsurface measurements that may be located some distance away. The uncertainty in estimated depths and thicknesses of geologic layers increases with increasing offset distances from the points of subsurface measurement. In this study the most important factors affecting ground shaking estimates appear to be the physical properties and thickness of the Quaternary surficial materials overlying the bedrock.

In this section, information on the compiled bedrock and surficial geology are briefly summarized, as well as the methods employed to estimate the depth and thickness of the surficial units.

Bedrock Geology

The term “bedrock” in the St. Louis area is used to describe those geologic formations of Paleozoic Era in the 29-quadrangle study area, which range in age between the Ordovician and

Pennsylvanian Periods. This bedrock is only sparsely exposed in the three pilot quadrangles. Most of the information about the underlying bedrock was developed from available borehole logs and previously mapped and interpreted areas. Information concerning the bedrock geology is referenced from the studies and maps prepared by ISGS, USGS, and MDNR (Denny, 2003; Denny and Devera, 2001; Harrison, 1997; Grimley and others, 2007; Lutzen and Rockaway, 1971). The bedrock is composed mainly of limestone, dolostone, chert, and sandstone. Pockets of individual sinkholes and karstic features in these limestones were identified by Goodfield (1965). In the hazard maps, however, karstic features were not taken into account because of the limited knowledge about the extent of these features.

Surficial Geology and Depth to Bedrock

The surficial geology of the St. Louis area varies widely, from thick alluvium in the broad Mississippi River valley to thin glacial drift (usually < 15 m), and to thick loess in the areas east of the Mississippi River, in Illinois. The loess is thickest (up to 29 m) at the bluffs immediately east of the Mississippi River valley and thins to the east and northeast (Fehrenbacher and others, 1986; Grimley and others, 2007). The modern river flood plains are comprised of alluvial sediment, mostly silts and clays, and a thick sequence of sands and gravels extending down to the bedrock (Goodfield, 1965). About 50 to 80 percent of the area in the Granite City, Columbia Bottom, and Monks Mound Quadrangles are contained within this Mississippi River alluvial valley (fig. 3).

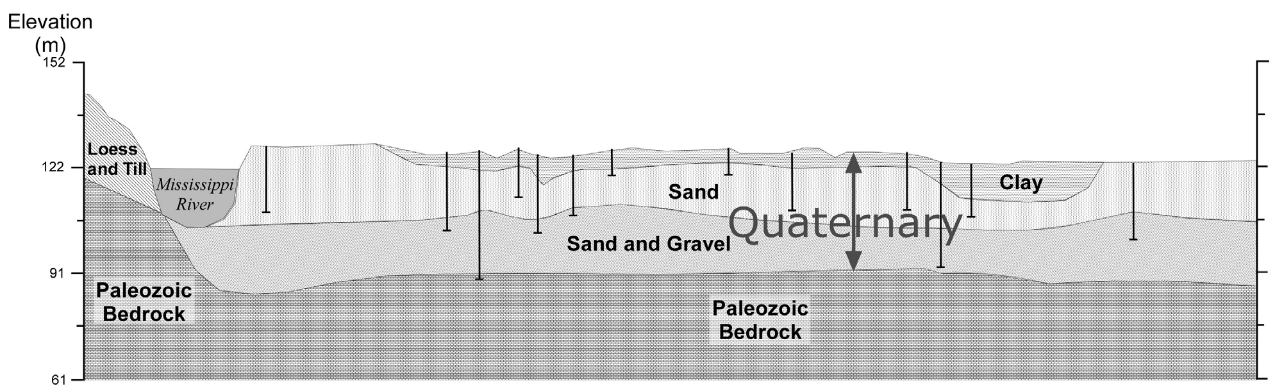

Figure 3. Schematic cross-section showing the surficial geology in the study area (after Grimley and others, 2007; Phillips and others, 2001). Thickness of Quaternary clay, sand, and gravel in the river lowland, overlying the Paleozoic bedrock, is constrained by borehole data (vertical black lines with horizontal bar at maximum depth).

In the study area the alluvial floodplains, being generally the area of lowest elevation, are identified as lowlands. Areas outside the floodplains generally covered by silt, till, loess, and some bedrock exposures are identified as upland regions. A Quaternary thickness map (or depth to bedrock) of the uplands and lowlands was prepared for the study area and used as input data in ground motion hazard calculations. Stratigraphic interpretations and geologic cross sections, used to estimate depth to bedrock, were prepared by MDNR and ISGS based on information gleaned from field exposures, geophysical surveys, and well logs (geotechnical, water wells, mining, and environmental; Missouri and

Illinois Department of Transportation (MoDOT and IDOT) and other private geotechnical agencies; Palmer and others, 2006, written commun.; Palmer 2006, personal commun.; Bauer 2006, personal commun.).

The Quaternary thickness map shows that the bedrock surface is thickest in the lowlands—generally about 30- to 40-m deep below the ground surface, and 0- to 10-m deep in the uplands. The bedrock surface changes most abruptly at the lateral margins of the modern day floodplain, which coincides with the boundary between lowlands and uplands. In limited sampling from seismic and boreholes the bedrock surface beneath the Mississippi River floodplain appears to be an even planated to slightly undulating surface, with an extensive area at an elevation of between 90 and 100 m. The greatest uncertainties about depth to bedrock exist in the deep alluvial valleys bordering major rivers, where there are few borings piercing the bedrock.

Shear-Wave Velocity Investigations in the St. Louis Metropolitan Area

The seismic hazard maps require accurate site-amplification calculations that largely depend on the estimated shear-wave velocity (Vs) of the materials underlying the site. In most site response hazard studies Vs has emerged as the one index property that is well correlated, inversely, with earthquake ground motion (Borcherdt, 1970, Wills and others, 2000). Researchers at Missouri S&T, Saint Louis University, MDNR, ISGS, and USGS have collaborated to collect, analyze, and interpret Vs measurements in the upper 50 m at over 100 locations in the St. Louis metropolitan area. These data constrained the St. Louis area seismic velocity model used in the earthquake hazard map calculations.

For these seismic studies we used small hammers to gently shake the ground either vertically to generate surface waves or horizontally to produce shear waves. Vs data was extracted from a variety of field methods including primarily seismic reflection/refraction and multi-channel analysis of surface waves (MASW) measurements, a few seismic cone penetrometer tests, one (Horseshoe Lake) site with downhole data, and one ultrasonic lab test of St. Louis limestone. As described above, bedrock depth around St. Louis was supplemented by existing drillers logs, some older oil exploration wells, and a detailed map of bedrock in downtown St. Louis compiled by URS-St. Louis. Subsurface seismic velocity models at each test site were constructed which were then used to develop the generalized shear-wave reference profiles for the St. Louis area.

Validation of the results by the different methodologies was achieved by comparing the surface-based methods (MASW and reflection/refraction) against existing borehole and downhole data from the same location or a nearby site. Seismic velocities of the soft sediments determined by surface-based methods differed by 5 to 30 percent from the downhole data. Discussions within the SLAEHMP about the thickness of highly weathered bedrock around St. Louis indicates that it is generally about 1 m thick for the limestone bedrock and that it is probably non-existent at the top of bedrock within the Missouri and Mississippi River floodplains where it has been scoured off. Thus, for the purposes of the earthquake hazard maps in St. Louis, the depth to the “distinct” alluvium or residuum contact with bedrock by reflection/refraction methods was determined to within about 10 percent of the downhole or borehole result. Vertical resolution limits of the surface-based methods are on the order of 1.5 to 3 m and thus capable of detecting layering that would influence ground motions at the 1- to 5-Hz frequencies of the proposed hazard maps.

Uplands on the Illinois side of the Mississippi River and part of the bedrock below the river on the east side is Pennsylvanian strata, which consists mostly of shales and claystones and thin layers of coal and limestone. The TWG has placed a 20-m thick weathered zone in these shales based on other weathering zones in shales in other parts of the state of Illinois.

Results of the Vs field studies show that the Paleozoic rock underlying softer alluvium and residuum in the St. Louis region is clearly identifiable in the reflection/refraction data at depths of generally 10 to 40 m. Indeed, in an analysis of St. Louis Advanced National Seismic System (ANSS) station recordings of a small earthquake, this important impedance boundary was shown to generate a prominent 2-Hz resonance in the 30-m thick alluvial section overlying bedrock in the Mississippi River floodplain (Williams and others, 2007). A clear difference exists in the Vs profiles between lowland sites and upland urban areas of St. Louis. Vs30 (average Vs to 30-m depth) values in the lowlands range from 200 to 290 m/s (NEHRP category D) and contrast with upland sites which have Vs30 values ranging from 410 to 785 m/s (NEHRP categories C and B). The lower Vs30 values and earthquake recordings in the floodplains suggest a greater potential for stronger and more prolonged ground shaking during an earthquake.

Despite all these measurements and extensive compilation, there are still 'holes' or areas of great uncertainty, especially about bedrock depth along the margins of the floodplain, in areas of the urban uplands not located near major highways and infrastructure. There is now discussion within SLAEHMP about gathering new data using inexpensive methods, to target these areas of uncertainty.

Reference Vs Profiles

In this section we summarize the methodology for determining two average Vs profiles for the study area. The methodology used is similar to that of Romero and Rix (2001, 2005) and Gomberg and others (2003). Based on similar characteristics, an average Vs profile was assigned to the lowlands (alluvium) and one to the uplands (loess, residuum, and till). Local analyses were performed to ascertain variations, uncertainties, and randomness associated with the Vs profiles. This study used 76 site-specific Vs profiles to compile characteristic profiles needed for the hazard calculations. In summary, characteristic Vs profiles were determined following a three-step procedure: 1) investigation of geology from the available borehole logs and estimations of the stratigraphy underlying each point of calculation, 2) determination of mean Vs (with uncertainties) from local Vs profiles, in one-meter depth increments, and 3) comparing the variations in Vs values with borings and known limiting parameters, such as depth-to-bedrock. See Karadeniz (2007) for more details on this methodology.

Site Amplification

The method used to calculate site amplification was similar to those employed in the Memphis seismic hazard maps, summarized in Cramer and others (2004). Time histories (see below) were input into the one-dimensional site-response software program SHAKE91 which calculates the propagation of the wave through the soil column and estimates the site-specific amplification factors and other parameters.

Anytime we perform a series of calculations that utilize a series of input variables, uncertainties with each of those variables will be compounded, leading to a greater range of uncertainty, bracketing the calculated/reported values. In the assessment of site amplification, uncertainties exist in the following input parameters: 1) natural variations in shear-wave velocity (for example, horizontal versus vertically propagating shear waves, effects of fracture intensity, weathering, and so forth), 2) natural variations in bulk density (especially, with preferential weathering), 3) the techniques used to estimate the depth and thickness of the soil layers, and 4) the differences in the earthquake time-history records used in the 1-D shaking analyses. When combined together, these uncertainties may cause large differences in amplification calculations. To account for this variability and uncertainties, a random sampling method is usually applied. Cramer and others (2004) used amplification distributions to account for the uncertainties associated with the amplification calculations. Cramer (2003) asserted that this method of calculating the hazard was the most dependable because it incorporates the uncertainties in the amplification factor. When a truly probabilistic site-specific ground motion is desired, the state-of-the-art approach should be used to estimate the site specific amplification factor distributions for use in the probabilistic calculations (Cramer, 2003; Cramer, and others 2004).

The site amplification calculations for peak ground acceleration, 0.2 s and 1.0 s spectral accelerations (SA) were performed using the site amplification code (siteampunc.f) provided by Chris Cramer (written commun., 2007). In this code, input site response parameters are randomly selected from a range of Vs profiles, dynamic soil properties, geologic boundaries, and a set of earthquake acceleration time-histories. The code then inputs these randomly selected parameters into Shake91 and calculates the response. The process for selecting input parameters is explained in the following sections and the results are summarized.

The amplification distributions were calculated based on a grid of 0.005° or for about every 500 m. There were a total of 1,974 grid points encompassing the three study quadrangles. For every grid point the site amplifications and distributions were calculated first, then the seismic hazard calculations. The amplification distributions were generated for two distinct geologic units (lowland deposits and upland deposits), and the 500-m grid is thought to be sufficient enough to capture the differences between these two units. The amplification values were then smoothed using GIS-based software and drawn as smooth color contours.

In this study, 12 recordings from six real earthquakes were selected in an attempt to capture the complexity of earthquake-time histories at epicentral distances close to 200 km. These recordings were obtained from the PEER strong-motion database, COSMOS strong-motion (http://db.cosmos-eq.org/scripts/default.plx), and Turkish General Directorate of Disaster Affairs (http://www.deprem.gov.tr/) strong-motion databases. In addition to these earthquake recordings, two synthetically generated M7.5 and M8.0 records, from Atkinson and Beresnev (2002), and M7.0 and M7.5 records using the SMSIM v. 2.2 code of Boore (2000), were selected. These synthetic recordings were chosen because they were felt to be more representative of the CEUS source characteristics and attenuation/damping properties. St. Louis is located approximately 200 km from the New Madrid and Wabash Valley Seismic Zones and, hence, recordings located at a distance of 180 to 220 km were selected, with magnitudes as close to 7.5 as possible.

To characterize the ground shaking in a fully probabilistic approach, the areal distribution of site amplification was required. To capture the amplification distributions, the above mentioned earthquake time-histories were scaled. This was accomplished on the actual ground-motion records at ten different shaking levels (0.01, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, and 1.0g) at specific frequencies (PGA, 0.2 s SA, and 1.0 s SA) to obtain input, or base rock ground-motions. An example of the 0.2 s SA probabalistic calculation is shown in figure 4. The Shake91 program was run for each of these shaking levels and the predicted site amplifications were determined for each level. In this study we used the shear modulus and damping ratio relations published by EPRI (1993).

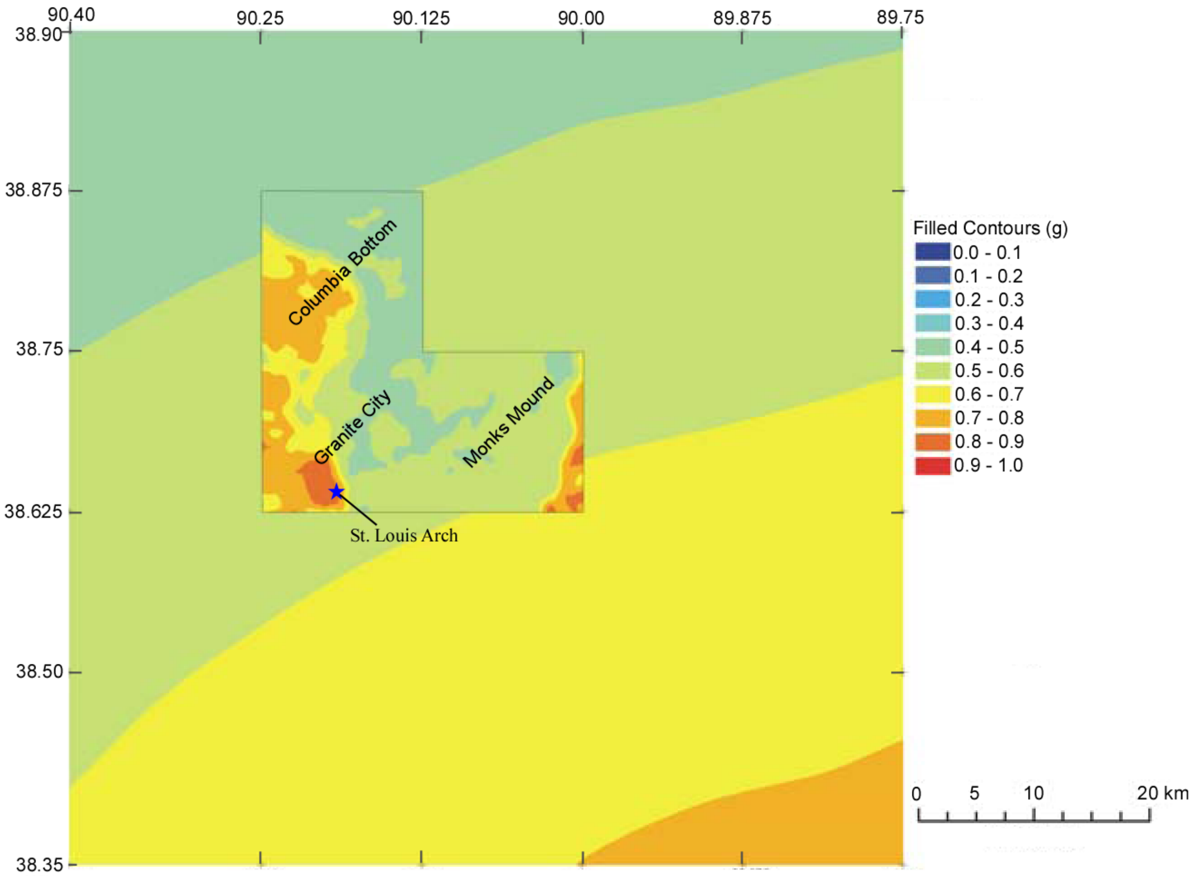

Figure 4. Probabilistic seismic hazard map showing 0.2-s SA(g) with two percent probability of exceedance in 50 years. The L-shape area represents the area of the three pilot quadrangles superimposed on the 2002 USGS National Seismic Hazard map for the same ground motion level (after Karadeniz, 2007).

Project Accomplishments

This study has so far accomplished the following:

1. Communication of interim project results occurred at several public outreach meetings, newspaper and television pieces, and field trips with an orientation toward St. Louis area earthquake hazard. A USGS Fact Sheet and USGS website focusing on the SLAEHMP were prepared. Several NEHRP-funded Final Technical Reports focusing on the St. Louis area have been completed including studies of surficial geologic mapping, liquefaction, borehole compilation, database construction, shear-wave velocities, and a comparison of 2002 versus 2008 hazard model changes on the three pilot quadrangles. A journal article on St. Louis area seismic velocities and site response has also been completed. In addition, two NEHRP-assisted Ph.D.'s on St. Louis earthquake hazards were completed by Missouri University of Science and Technology students.
2. Distribution of the surficial material thickness in the St. Louis area was determined with respect to recognized (mapped) surficial geologic units. For this purpose subsurface data from 1,500

3. Reference Vs profiles were created from the shear-wave velocity measurements taken in the St. Louis region for this study. The shear-wave velocity statistical analysis included an assessment of the variations in the measurements and the data interpretation. Reference Vs profiles were prepared for the two dominant types of surficial conditions (lowlands and uplands) in the study area using 5-m depth increments. These reference profiles were the first ones generated for the St. Louis area.
4. Site-amplification factors were estimated for the areas of the three pilot quadrangles, with respect to earthquake-shaking level and these data were summarized in map form. These site-amplification distributions were calculated for upland and lowland sites. Site-amplification analyses were carried out accounting for the uncertainties associated with each of the input parameters.
5. Hazard analyses were performed for PGA, 0.2 s SA and 1.0 s SA, accounting for the uncertainties associated with the results of the site amplification estimates. These results are unique for the area because the hazard analyses were based on a fully-probabilistic approach, where site amplification distributions were incorporated into the probabilistic calculations instead of just using the median site amplification value.

Conclusions

The following conclusions have been reached for the preliminary estimations of site amplification and the associated hazard estimations. These conclusions are subject to change or revision as new data, information, and observations become available.

1. In the St. Louis area the modern floodplains (lowlands) and the alluvial thickness is fairly uniform, between 30 and 40 m, thinning to as little as 5 m at the lateral margins bounding the uplands. The thickness of the Quaternary deposits in the uplands varies considerably between 5 and 73 m.

2. The median shear-wave velocity of Quaternary alluvium (lowland deposits) is 200 m/s, and upland deposits have an average velocity of 208 m/s.

3. Natural variations and physical characteristics of the Quaternary deposits overlying the Paleozoic bedrock in the St. Louis area exerts a significant influence on the amplitude and frequency characteristics of the earthquake ground motions at the surface.
4. The measured Vs in lowlands and uplands appear to be a simple function of depth and not their geologic age.
5. Accurate estimates of Quaternary material thickness are essential to allow accurate predictions of site amplification, especially for 1.0-s SA.

The following results apply to the three Pilot Quadrangles study area: Columbia Bottom, Granite City, and Monks Mound.

6. Lowland and upland sites exhibit distinct amplification behaviors for small ground-motion levels (<0.01g) for all ground motion parameters: PGA, 0.2-s SA and 1.0-s spectral acceleration.
7. Although differences in site amplification between lowlands and upland sites tend to decrease with increasing ground motion (up to 0.5g), low strain ground motion recordings of earthquakes in

8. Lowland sites exhibited deamplification of ground motions when the rock accelerations exceed 0.5g. Upland sites did not exhibit deamplification at any input acceleration (between 0.01 and 1.0g).
9. The two most important parameters affecting site amplification estimates were the input-time histories and the thickness of Quaternary deposits.
10. Lowlands and uplands exhibit contrasting shaking characteristics for each of the ground motion parameters and earthquake scenarios considered. Uplands are characterized by large accelerations at 0.2-s-period SA for all levels of probability, consistently more than 50 percent greater than in the lowlands. This means that on upland sites, earthquake forces may be most severe for short period structures (less than five stories high).
11. Lowlands are characterized by large accelerations at 1.0-s-period SA for all levels of probability. This means, in the lowlands, earthquake forces may also be severe for long period structures (greater than 10 stories).
12. The PGAs are similar for the lowlands and uplands sites for all probabilistic ground-motion levels.
13. When compared to the USGS National Maps, the probabilistic hazard levels calculated in this study for lowland sites exhibit zero to 200 percent greater ground motion levels for PGA, and between 20 percent smaller to 150 percent greater ground-motion levels for 0.2-s SA; and, 100 to 260 percent greater ground-motion levels for 1.0-s SA.
14. When compared to the USGS National Maps, the probabilistic hazard levels calculated in this study for upland sites show zero to 300 percent greater ground-motion levels for PGA, 200 to 250 percent greater ground-motion levels for 0.2-s SA and 0 to 175 percent greater ground-motion levels for 1.0-s SA.
15. The results of the deterministic scenarios suggest that the hazard levels for 0.2-s SA in uplands sites are approximately 15 percent higher than for lowland sites. The lowland sites exhibit consistently higher acceleration levels at 1.0-s SA, similar to the probabilistic maps.

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