Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 704

THE ST. LOUIS AREA EARTHQUAKE HAZARDS MAPPING PROJECT - SLAEHMP

SLAEHMP Technical Working Group[1]

ABSTRACT

The St. Louis Area Earthquake Hazards Mapping Project is a major urban hazard mapping effort supported in part by the U.S. Geological Survey's (USGS) Earthquake Hazards Program, External Research Support. The goal of the project is to provide state-of-the-art urban seismic hazard maps for the greater St. Louis area in Missouri and Illinois that can be used in land-use planning, public policy making, and private sector decision making. Urban seismic hazard maps that include the effects of local geology have been completed for three initial quadrangles and maps for additional quadrangles are being prepared. Liquefaction potential maps for 12 quadrangles in the Mississippi and Missouri River flood plains have also been completed. Surface mapping and subsurface geological, geophysical, and geotechnical information form a three-dimensional geologic database. Reference profiles were generated from shear-wave velocity (Vs) measurements for the uplands (loess/till) and lowlands (alluvial) portions of the study area. Site amplification ranges (distributions) are then generated by the randomization of the Vs profile, dynamic properties, and appropriate input ground motions and these were used to generate probabilistic and scenario ground motion hazard maps.

For PGA and 0.2 s Sa, the resulting urban hazard maps show increased ground motion hazard in the uplands, which are thinly covered by loess. The 30-50 m thick alluvium lowlands show similar ground motion relative to the 2008 USGS national seismic hazard maps. For 1.0 s Sa, the urban seismic hazard maps show the reverse - greater amplification on lowlands soil than upland soils. Holocene alluvial units in river valleys and flood plains are the most susceptible to liquefaction. Late Pleistocene glacio-fluvial outwash has a moderate-to-low susceptibility and upland loess deposits have a very low susceptibility. Because many transportation routes, power, petrochemical and gas transmission lines, population centers, and levee structures exist on the highly susceptible Holocene alluvium, parts of the greater St. Louis area are at significant potential risk from seismically induced liquefaction and related ground deformation. Additionally, where infrastructure transitions from lowlands to uplands are areas of significant potential risk due to rapid spatial changes in the level of ground shaking.

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Introduction

The St. Louis Area Earthquake Hazards Mapping Project (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 are 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). The goal of the St. Louis project is to produce practical hazards maps and internet-accessible products that can be used by geoscientists, design communities, and city and county planning agencies.

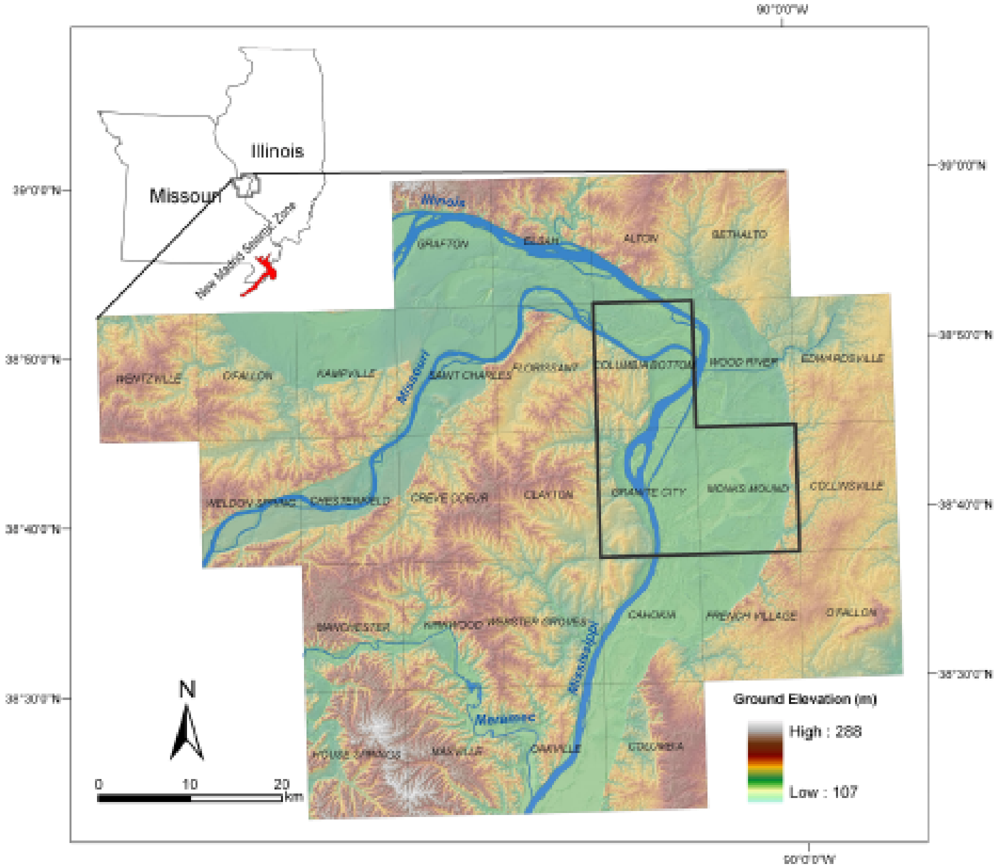

Figure 1. Twenty-nine USGS quadrangle study area of SLAEHMP. Black outline of 3 quadrangles shows the pilot study area. Inset map shows location of the study area in Missouri and Illinois relative to the New Madrid seismic zone.

In 2004 the USGS organized SLAEHMP because of the earthquake hazard potential in St. Louis from earthquakes in other parts of the Midwest. The project is guided by a Technical Working Group (TWG) consisting of earth scientists and engineers from local firms, universities, and government agencies. The study area encompasses about 4,000 square km across 29 USGS 7.5-minute quadrangles (Fig. 1). The objectives of this project are to: 1) create detailed maps of earthquake hazards in the St. Louis area, 2) create a database of geologic and geotechnical information, and 3) enlist input from stakeholder and end users of the hazard maps. An initial goal, which is largely accomplished, 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 (Cramer et al., 2004, 2006). Detailed surficial geologic mapping of the Illinois part of the study area is complete and the Missouri part will probably be completed over the next 3-4 years, but a complete set of hazard maps for a 12-15 quadrangle subset of the 29-quadrangle study area adjoining the three pilot quads should be completed in 2011.

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 and 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. Earthquake time histories were taken from catalogs of observed recordings, including Mt. Carmel, plus synthetic histories for the central U.S (Cramer, 2009).

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 effecting ground shaking estimates appear to be the physical properties and thickness of the Quaternary surficial materials overlying the bedrock.

Site Amplification

The method used to calculate site amplification is similar to those employed in the Memphis seismic hazard maps, summarized in Cramer et al. (2004, 2006). The site amplification calculations for peak ground acceleration (PGA), 0.2 s and 1.0 s spectral accelerations (Sa) were performed using SHAKE91 (Idriss and Sun, 1992). SHAKE91 has been validated and calibrated for CEUS soil conditions to avoid over attenuation at high ground motions as described in Cramer (2006). 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 (Karadeniz, 2007). Site amplification distributions for each grid point are derived from 100 Monte Carlo randomizations of these input parameters.

The amplification distributions are 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 pilot quadrangles. For every grid point the site amplifications and distributions were calculated first, followed by the probabilistc seismic hazard calculations (Cramer, 2003, 2005). 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.

Liquefaction Potential

Liquefaction hazard studies for the St. Louis area were conducted by Pearce and Baldwin (2008) and Chung and Rogers (2009). These studies mainly focused on the Mississippi River flood plain in the St. Louis area. The Pearce and Baldwin study used the Simplified Procedure method (Seed and Idriss, 1971), which was modified by Cetin et al. (2004) to estimate the liquefaction susceptibility of deposits. This method uses the Standard Penetration Test (SPT) blow count data in relation to earthquake-induced cyclic shear stresses. The products of the Pearce and Baldwin study are liquefaction susceptibility maps. Chung and Rogers used the Liquefaction Potential Index (LPI) method of Holzer et al. (2006). The products of the Chung and Rogers study are liquefaction potential maps based on the probability of exceeding a specified LPI value calculated for the soil column for each site for the shaking level produced by a specific earthquake magnitude (proxy for duration of shaking).

Data

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 Paleozoic geologic formations in the 29-quadrangle study area, which range in age between the Ordovician and Pennsylvanian Periods. 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 Illinois State Geological Survey (ISGS), USGS, and Missouri Department of Natural Resources (MDNR) (Karadeniz et al., 2009). The bedrock is composed mainly of limestone, dolostone, chert, and sandstone on the Missouri side and shale with some limestone on the Illinois side. Pockets of individual sinkholes and karst features in these limestones were identified by Goodfield (1965). In the hazard maps, however, karst features were not taken into account because of the limited knowledge about the extent of these features and how they would react to specific magnitude events.

Surficial Geology

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) or exposed bedrock, and to thick loess in the areas east of the Mississippi River, in Illinois. In the three pilot quadrangle area 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. 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. 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. 2).

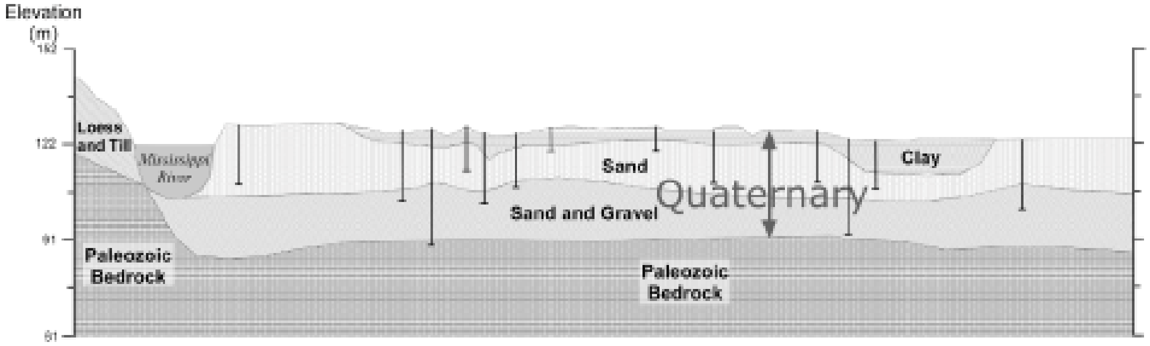

Figure 2. Schematic cross-section showing the surficial geology in the study area. Thickness of Quaternary clay, sand, and gravel in the river lowland, overlying the Paleozoic bedrock, is constrained by borehole data (vertical black lines with horizontal bar at maximum depth).

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 (loess), till, and some bedrock exposures are identified as upland regions. A Quaternary thickness map (or depth to Paleozoic 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 (Karadeniz et al., 2009).

The Quaternary thickness map shows that Paleozoic bedrock depth is greatest in the lowlands—generally about 30- to 40-m deep below the ground surface, and shallowest in the uplands, 0- to 10-m deep. 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 studies and boreholes the bedrock surface beneath the Mississippi River floodplain appears to be a planar-to-slightly-undulating surface, with an extensive area at an elevation (AMSL) of between 90 and 100 m. The greatest uncertainties about depth to bedrock exist in the deep alluvial valleys bordering major rivers, particularly at their margins where they transition to the uplands, where there are few borings piercing into bedrock.

Velocity Investigations

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 et al., 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 (Karadeniz et al, 2009). For these seismic studies we used 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. Data on 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 and used to develop reference Vs profiles for the St. Louis area.

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). Paleozoic bedrock outcrops are hidden by urban development and are not considered in this study. The lower Vs30 values and earthquake seismogram recordings in the floodplains suggest a greater potential for stronger and more prolonged ground shaking during an earthquake.

Reference Vs Profiles

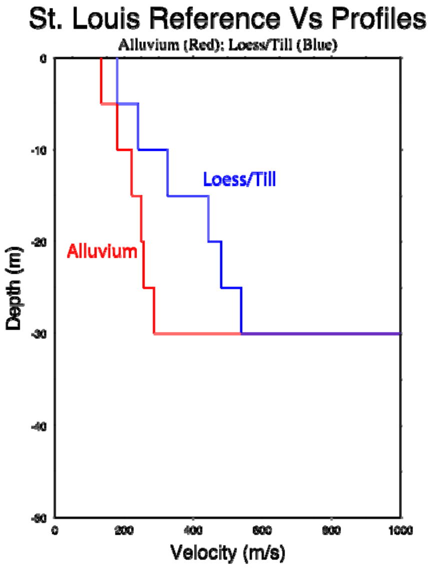

Figure 3. SLAEHMP Vs reference profiles.

Two average Vs profiles, based on surface geology type, have been developed and used in the hazard calculations for the pilot quadrangles. The methodology used to create these reference profiles is similar to that of Romero and Rix (2001, 2005) and Gomberg et al. (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 (Karadeniz, 2007). 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 (Karadeniz, 2007). Fig. 3 presents these two reference profiles. For site amplification distribution calculation at a site, the reference profiles were truncated at the depth indicated by the depth-to-bedrock map.

Results

Probabilistic Seismic Hazard Maps

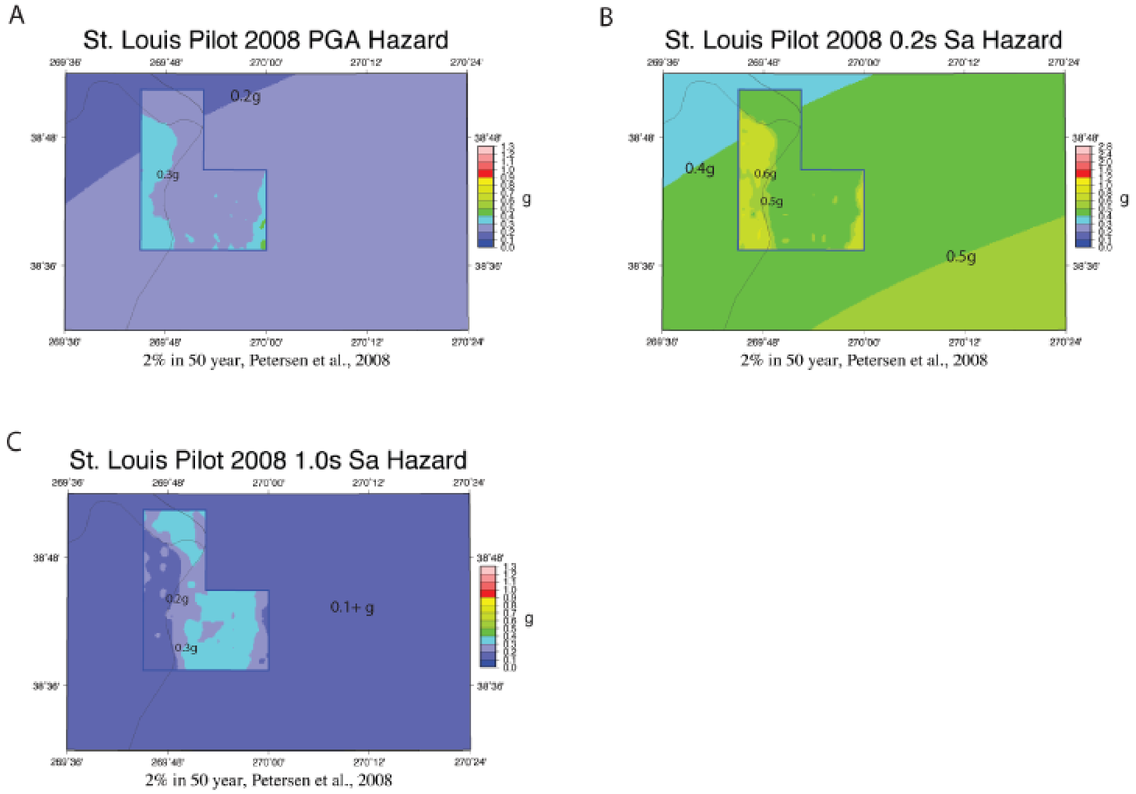

Figure 4. 2%-in-50-year seismic hazard maps for SLAEHMP pilot quadrangles inset into 2008 USGS national seismic hazard maps for (a) PGA, (b) 0.2 s Sa, and (c) 1.0 s Sa.

Seismic hazard maps for the St. Louis pilot quadrangles are shown in Fig. 4 for peak ground acceleration (PGA) and 0.2 and 1.0 s spectral acceleration (Sa) (Cramer, 2009). The background in these hazard maps is the corresponding 2008 USGS national seismic hazard map, which is for a constant soil condition (Petersen et al., 2008). The 2008 national seismic hazard model was also used to generate the pilot quadrangle probabilistic maps. Fig. 4 clearly demonstrates the impact of including the effect of the local soils. For short periods (PGA, 0.2 s Sa), the thinner, stiffer upland soils amplify more than the thicker, softer lowland alluviums due to nonlinear deamplification in the alluvium. For long periods (1.0 s Sa), the opposite is true: thicker lowland soils amplify ground motions and thin upland soils are too thin to amplify long-period ground motions. Magnitude 7 events at about 200 km distance (New Madrid) are the predominant influence at all periods. M5 and M6 events at distances of less 50 km are less significant contributors.

Scenario ground-motion hazard maps (not shown due to space limitations) have also been generated for a M7.7 earthquake 200 km southeast of St. Louis on the NE (closest) segment of the New Madrid Seismic zone and a M6.0 earthquake 40 km east-southeast of downtown St. Louis in the Shoal Creek paleoliquefaction site. These scenario maps for PGA, 0.2 s, and 1.0 s show similar ground shaking trends as the probabilistic maps.

Liquefaction Potential Maps

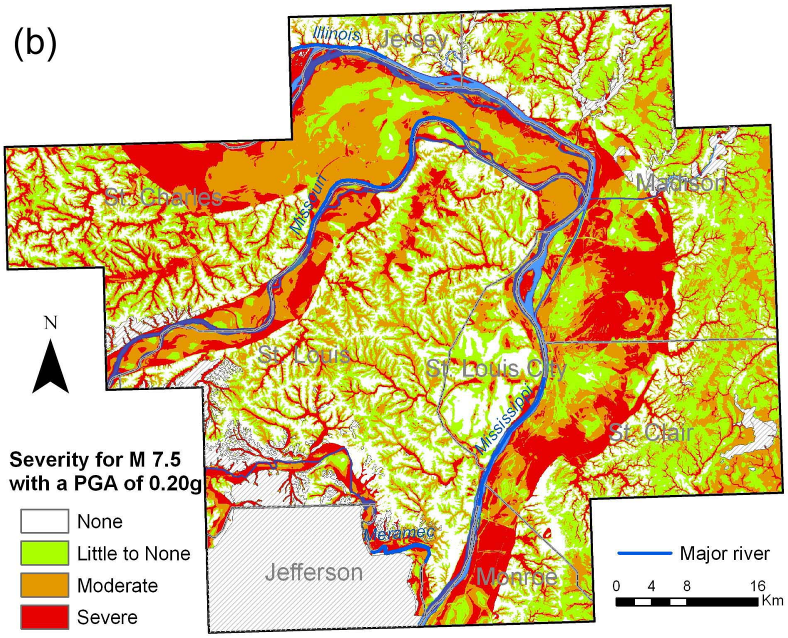

Figure 5. Liquefaction potential map for a M7.5 earthquake (effecting shaking duration) with a uniform 0.2 PGA input ground motion. This liquefaction potential map is not for a specific scenario event.

Fig. 5 presents one of the results from Chung and Rogers (2009). The map shown is based on LPI values for a M7.5 earthquake (proxy for duration of shaking) with an input PGA of 0.20 g everywhere. The liquefaction potential map is not tied to a specific real earthquake scenario, but to a specific level of input ground motion everywhere from a specific magnitude earthquake, which is a proxy for ground shaking duration. Clearly, major river valleys and tributary rivers and streams have a higher potential for liquefaction than the surrounding upland hills.

Impacts

From Fig. 4 we see strong ground shaking gradients at the uplands/lowlands transition at the edge of river valleys, particularly for the Mississippi River valley. These geologic transitions are areas of significant potential risk to infrastructure crossing them due to these gradients in shaking intensity. The sign of these gradients are opposite for short and long periods, but still present increased risks in both period ranges.

From Fig. 5 we see that the lowlands are areas of increased liquefaction as well as long period shaking hazard. Many transportation routes, power, petrochemical and gas transmission lines, population centers, and levee structures exit on these highly susceptible Holocene alluvium deposits (Chung and Rogers, 2009). These parts of the St. Louis area are at significant potential risk from seismically induced liquefaction and related ground failure.

Acknowledgements

The authors gratefully acknowledge helpful reviews by Christine Powell, David Perkins and Steve Hartzell.

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