FINAL TECHNICAL REPORT

LIQUEFACTION SUSCEPTIBILITY AND PROBABILISTIC LIQUEFACTION POTENTIAL HAZARD MAPPING, ST. LOUIS, MISSOURI AND ILLINOIS

Recipient:
William Lettis & Associates, Inc., 1777 Botelho Drive, Suite 262, Walnut Creek CA 94596
Phone: (925) 256-6070; Fax: (925) 256-6076; URL: www.lettis.com

Principal Investigators:
Justin T. Pearce, John N. Baldwin
Email: pearce@lettis.com; Email: baldwin@lettis.com

Contributor:
Jeff Hoeft
William Lettis & Associates, Inc., 1777 Botelho Drive, Suite 262, Walnut Creek CA 94596

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Justin T. Pearce, John N. Baldwin, and Jeff Hoeft
William Lettis & Associates, Inc., 1777 Botelho Drive, Suite 262, Walnut Creek CA 94596
phone: (925) 256-6070; fax: (925) 256-6076; email: pearce@lettis.com; baldwin@lettis.com

ABSTRACT

This research builds on and expands recently-completed liquefaction susceptibility mapping of five quadrangles including downtown St. Louis area (Pearce and Baldwin, 2004). This research completed construction of seven (7) new liquefaction susceptibility maps and, with the inclusion of our five existing susceptibility maps, and construction of twelve (12) new probabilistic liquefaction potential maps. In total, the study encompasses twelve U.S.G.S. 7.5-minute quadrangles that include St. Louis, East St. Louis and the surrounding metropolitan area. Much of these areas are underlain by saturated granular Holocene fluvial deposits of the Mississippi, Missouri, and Meramec Rivers (Harrison, 1997), as well as artificial fill material that is susceptible to earthquake-induced liquefaction. Coupled with the 1811-1812 earthquakes, St. Louis also has experienced multiple historical earthquakes from more local seismic sources (e.g. within 80 to 110 km) some with earthquake magnitudes up to **M**5 (e.g., April 18, 2008), and MMI between V-VI. The potential for liquefaction depends not only on the susceptibility of a deposit to liquefy, but also depends on the estimated ground motion to exceed a specified threshold required to initiate liquefaction. Probabilistic liquefaction hazard potential maps are based on liquefaction susceptibility maps, and directly incorporate numerically modeled earthquake ground motion data (PGA) for different probabilities of occurrence (return intervals). Thus, this effort directly results in hazard maps for the probabilistic liquefaction potential hazard within the greater metropolitan St. Louis area.

We employ detailed surficial geologic mapping in conjunction with a quantitative geotechnical analysis (Simplified Procedure) to evaluate and classify the relative susceptibility to liquefaction of the Quaternary deposits. From the mapping we differentiate four primary geologic units: Artificial fill, Holocene alluvium, Pleistocene glacio-fluvial alluvium, and Pleistocene loess and other non-alluvial deposits. Not surprisingly, the results of the susceptibility analysis show that Holocene alluvial units are the most susceptible to liquefaction. Liquefaction triggering thresholds for mapped deposits were estimated based on the Simplified Procedure analysis. The PGA values from the National Seismic Hazard Mapping Program served as the basis for the probabilistic evaluation of liquefaction potential. This research evaluated two earthquake ground motion scenarios: the 2% probability of exceedance in 50 years (~2500 yr return period), and 10% probability of exceedance in 50 years (~500 yr return period). The results of the analyses show that while much of the surficial deposits are susceptible to liquefaction, the PGA values for the 10% in 50 years probability appear to be deficient to trigger liquefaction, whereas stronger (i.e. more conservative) ground acceleration values for the 2% in 50 years probability have sufficient magnitudes to trigger liquefaction within much of the study area. Additionally, the result of the 2% probability in 50 year analysis indicates: (1) liquefaction trigger thresholds are exceeded within much of the study area, however the liquefaction potential decreases northerly across the region with PGA; and, (2) the hazard is predominantly controlled by the magnitude of co-seismic strong ground motion and, to a lesser degree, variability of surficial deposits.

The results of this study provide data needed to effectively evaluate and manage liquefaction hazards in the St. Louis area, and thus will contribute to the USGS and FEMA loss reduction efforts in the greater central United States. Although these hazard maps are based on detailed geologic maps and available geotechnical information, the hazard maps are regional in scope and should not be considered or used as a substitute or replacement for site-specific geologic or geotechnical investigations. Quantitative evaluation of the possible amounts and locations of permanent ground surface deformation from the potentially liquefaction-triggering ground motions (e.g., differential settlement, lateral spread), as well as incorporation of next generation attenuation models is a necessary future research path that will add value and understanding of the overall seismic hazard of the greater metropolitan region.

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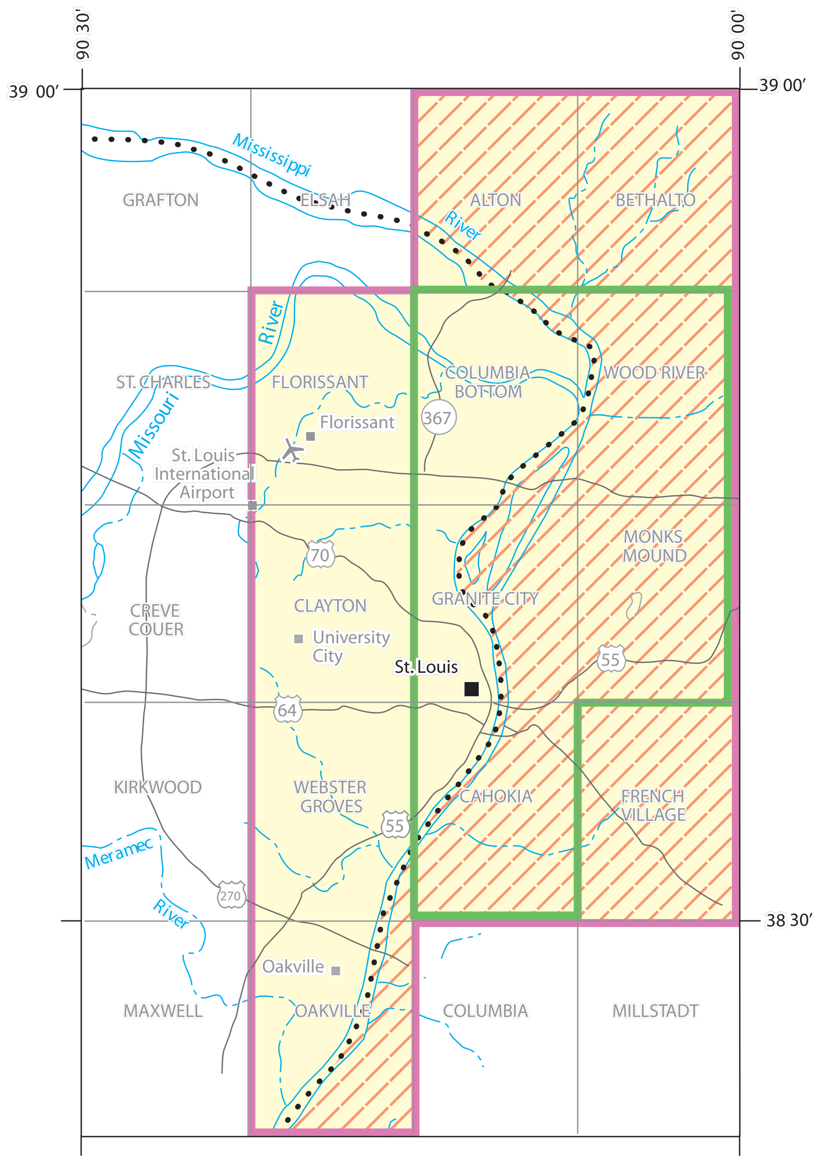
1.0 INTRODUCTION

This final technical report presents the results of a detailed study to assess the relative susceptibility of Quaternary geologic deposits to earthquake-induced liquefaction near St. Louis, Missouri, and the probabilistic liquefaction potential of those deposits based on estimated triggering thresholds and analysis of peak ground accelerations (PGA). The primary goal of this research is to characterize the probability of liquefaction of late Quaternary sediments and artificial fill in and around St. Louis, Missouri and Illinois, based on two earthquake ground motion scenarios (Frankel et al., 2002). The result of the geologic characterization and quantitative analysis is the construction of GIS-based, 1:24,000-scale, liquefaction susceptibility and probabilistic liquefaction potential maps. Specifically, the study area encompasses twelve 7.5-minute quadrangles in the greater St. Louis area and surrounding communities such as Metro East, Illinois, and downtown St. Louis, Missouri (Alton, Bethalto, Florissant, Columbia Bottom, Wood River, Clayton, Granite City, Monks Mound, Webster Groves, Cahokia, French Village, Oakville; Figure 1). To avoid confusion, the study area will be referred to in this report informally as the "St. Louis region". This study evaluates the probabilistic liquefaction potential through analysis of the two ground motion scenarios: the 2% chance of exceedance in 50 years (~2500 year "return interval"), and 10% chance of exceedance in 50 years (~500 year "return interval").

Much of the low-lying St. Louis region (Figure 1) is underlain by a substantial thickness (up to 125 feet) of Holocene and Pleistocene alluvial floodplain and pro-glacial outwash deposits of the Mississippi and Missouri Rivers. These unconsolidated granular materials are potentially susceptible to liquefaction during large earthquakes from nearby potentially undetected seismic sources, or possibly even more distant, larger seismic sources, such as the New Madrid seismic zone (NMSZ), the Wabash Valley Seismic Zone (WVSZ), and the Commerce Geophysical Lineament (CGL) (e.g., Wheeler and Perkins, 2000; Hermann et al., 1999, Atkinson and Beresnev, 2002; Pearce and Baldwin, 2004). Experience from historical earthquakes has demonstrated that late Quaternary sediments of saturated, granular materials (i.e. alluvium), as well as non-engineered fill, are highly susceptible to liquefaction (Tinsley and Holtzer, 1990). Furthermore, levees constructed on or composed of these granular materials could potentially fail by liquefaction during large earthquakes. Regional (1:100,000 scale) hazard mapping of the St. Louis area was completed in 1995 by the Missouri Department of Natural Resources Geological Survey and Resource Assessment Division (now MGS) and shows large areas as potentially liquefiable along the Missouri and Mississippi rivers and substantial areas in the urbanized "upland" tributary drainages (Hoffman, 1995). Our research refines the initial hazard assessment of Hoffman (1995) by developing detailed Quaternary geologic mapping, by incorporating subsurface geologic and geotechnical data, and by analyzing ground motion estimates to quantitatively assess liquefaction potential within in the greater St. Louis area.

Previous reconnaissance studies confirmed evidence of paleoliquefaction in the region along tributaries to the Missouri and Mississippi Rivers, for example the Meramec River, a large tributary to the Mississippi River, is shown on the 1:100,000-scale hazard map of Hoffman (1995) as having variable or unknown liquefaction hazard. In contrast, field evidence for paleoliquefaction has been documented in the Meramec River sediments (e.g., Tuttle, 1999), and other drainages (i.e. Kaskaskia River, Shoal Creek; McNulty and Obermeier, 1999). However, to the best of our knowledge, no comprehensive characterization of the geotechnical properties of similar fluvial deposits, or detailed maps of liquefaction susceptibility or probabilistic liquefaction potential, exist for the greater St. Louis area prior to this study. Therefore, a distinct need exists for a detailed study of liquefaction hazard to provide information to communities, agencies, and scientific body for improved seismic hazard evaluation, planning and mitigation strategies.



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Explanation

Quaternary surficial geologic maps developed by this study

Quaternary surficial geologic maps developed by Illinois State Geologic Survey

Liquefaction susceptibility hazard mapping (NEHRP 03HQGR0029)
(Pearce and Baldwin, 2004; 2005)

Liquefaction susceptibility and probabilistic liquefaction potential hazard mapping
(NEHRP 05HQGR0063)

• • • • • State border (Missouri on west, Illinois on east)

Figure 1. Location map and quadrangle index of liquefaction hazard mapping in St. Louis area, Missouri and Illinois

Liquefaction is not a randomly occurring phenomenon; liquefaction tends to be restricted to deposits with certain geologic and hydrologic conditions (Youd, 1973). Since these conditions can be identified, delineated, and mapped (e.g. Youd and Perkins, 1987), planners, federal and state agencies, and individuals can prepare for and mitigate the effects of liquefaction. For example, if local governments have information on areas of possible liquefaction susceptibility hazard, they can require that site-specific analyses be performed prior to new development and appropriate engineering mitigation be incorporated into project design.

In this report, in addition to the presentation of the probabilistic liquefaction potential hazard maps, we describe the methods, data, analysis and criteria used to evaluate, and then integrate, each component that are used to construct the maps (Figures 2 and 3). Subsurface deposit properties such as soil type, estimated fines content, and relative density, are characterized through borehole logs, coring logs, and Standard Penetration Test (SPT) blow count data. Regional groundwater conditions are assessed based on existing data and a scenario depth-to-groundwater map was developed for use in the quantitative liquefaction analysis. Thus, the liquefaction hazard maps are based on: (1) existing and newly completed 1:24,000-scale Quaternary geologic maps for the study area; (2) characterizing regional depth to groundwater data; (3) evaluating liquefaction triggering thresholds using the “Simplified Procedure” devised by Seed and Idriss (1971), refined by Cetin et al. (2004); and (4) analyzing the triggering threshold estimates against ground motion values at two levels of probability (Frankel, et al., 2002). The location and extent of surficial deposits are characterized by Quaternary geologic mapping. The final map products are delivered as digital 1:24,000-scale GIS map layers. These maps can be used to improve the assessment of liquefaction hazards in St. Louis and allow communities to better plan and mitigate the effects of liquefaction on the built environment.

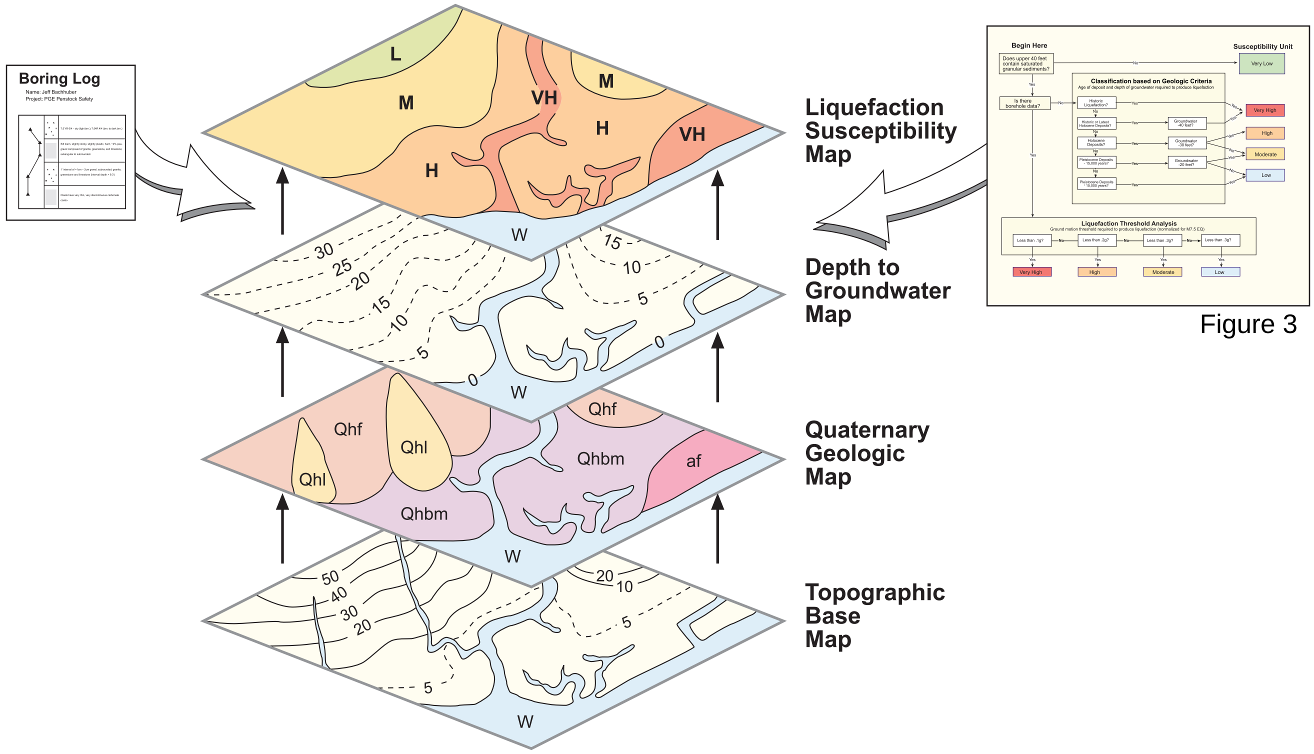

Figure 2. Data sources and integration procedures to produce a liquefaction susceptibility map

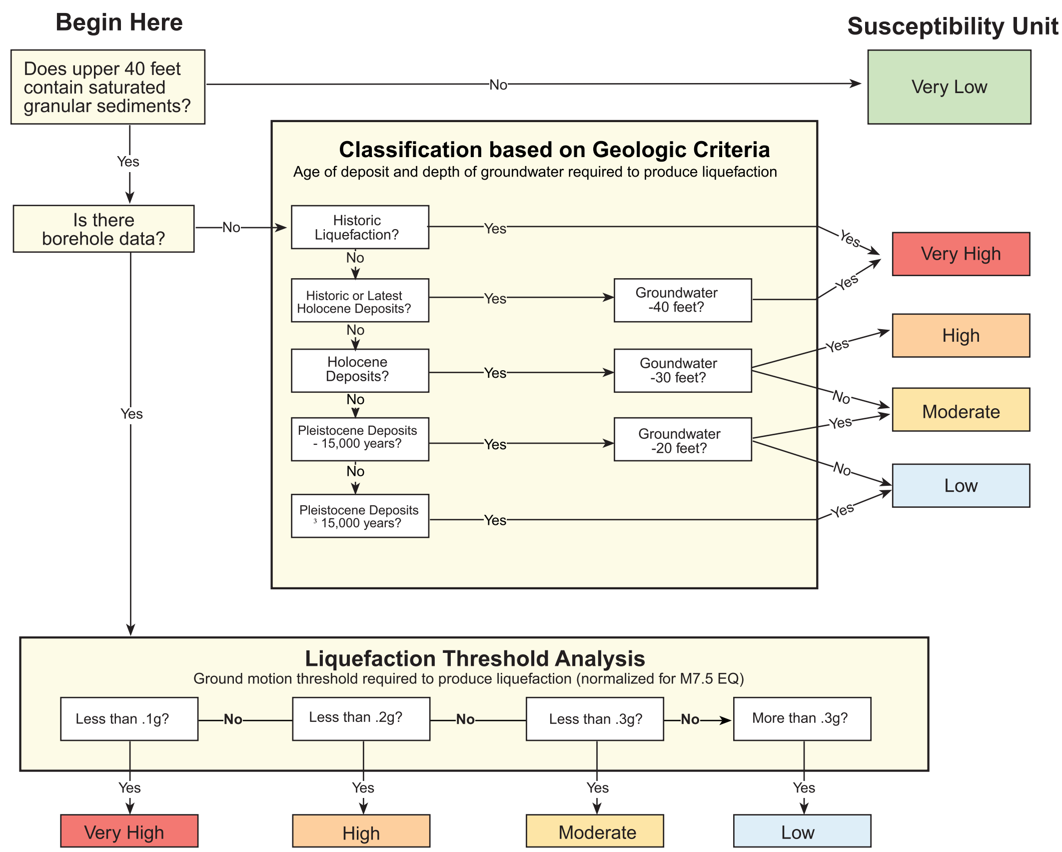

Figure 3. Decision flow chart for evaluation of liquefaction susceptibility using ground motion thresholds required to produce liquefaction, normalized for a 7.5 magnitude earthquake (Hayden, Lloyd, and Haydon, 1999)

2.0 BACKGROUND

Liquefaction-related ground failures historically have caused extensive structural and lifeline damage in urbanized areas around the world. Recent examples of these effects include damage produced during the 1989 Loma Prieta, 1994 Northridge, 1995 Kobe, 1999 Izmit, and 2001 India earthquakes. These, and other historical earthquakes such as the 1811-1812 New Madrid earthquakes, show that the occurrences of co-seismic liquefaction, and thus the distribution of liquefaction-related damage, is generally restricted to areas that contain low-density, saturated, near-surface (<50 feet depth) granular sediments susceptible to liquefaction, that are in regions where seismic ground motions exceed a triggering threshold level. Large portions of the St. Louis metropolitan area, including extensive areas of industrial, commercial, and residential development, are underlain by granular Holocene and latest Pleistocene alluvial sediments of the Missouri and Mississippi Rivers (Goodfield, 1965; Harrison, 1997; Grimley and Lepley, 2001; Pearce and Baldwin, 2004). Furthermore, the St. Louis area has been expanding in terms of population, developed areas, and infrastructure, increasing the vulnerability to loss of life and property damage into a larger geographic area. As of 2000, St. Louis County ranked 34th in total population of all counties within the United States, with just over 1,000,000 residents. Collectively, within Illinois and Missouri the entire study area consists of an even larger population. Conjunctively with the population, a preponderance of police, fire, and emergency response stations are located within the study area, as well as key pipelines, highways, bridges, and other lifelines and infrastructure (Hoffman, 1995).

Paleoliquefaction studies in the region have shown that many of the tributaries of the Mississippi River, such as the Meramec, Kaskaskia, and Big Rivers provide exposures of earthquake-related liquefaction deformation (e.g. sand blows) interpreted to have been caused by the New Madrid 1811-1812 earthquakes or earlier events from unknown seismic sources. According to historical accounts, St. Louis suffered considerable damage from the 1811-1812 earthquakes, including structural damage to dwellings such as cracked houses and toppled brick chimneys (St. Louis University Earthquake Center, 2004). The region has experienced other, less infamous, earthquake events (Figure 4) that were of sufficient ground shaking intensity to cause structural damage, such as the:

(1) January 1843 MMI VI event (estimated magnitude 6.0, northeast Arkansas source) that toppled chimneys in the area;
(2) April 1917 MMI VI event (estimated magnitude 5.0, Ste Genevieve, Missouri source) that “threw horses to pavement in St. Louis” and caused damage to houses and chimneys;
(3) November 1968 MMI V-VII event (estimated magnitude 5.5, southern Illinois source), that shook and moved furniture, cracked walls, and toppled chimneys (St. Louis University Earthquake Center, 2004)
(4) April 18, 2008 event, (estimated 5.2 magnitude; Figure 4).

2.1 Previous Liquefaction Studies

Historical and modern records clearly indicate that the region is subject to repeated strong ground shaking, and the geological conditions are sufficient for liquefaction to occur. Regional (1:100,000-scale) hazard mapping of the St. Louis area was completed by the Missouri GSRAD (Hoffman, 1995), and is a useful screening-level map of the hazard. However, this hazard mapping did not evaluate the differences in relative liquefaction susceptibility that exist due to the differences in geologic depositional environment, texture, and age. The regional liquefaction hazard mapping performed by our study predominantly relies on characterizing these criteria to relate surficial geology to liquefaction susceptibility (Figures 2 and 3). Semi-empirical methods for estimating liquefaction susceptibility such as the Simplified Procedure (Seed and Idriss, 1971; NCEER, 2001, Cetin, 2004) are based on the site-

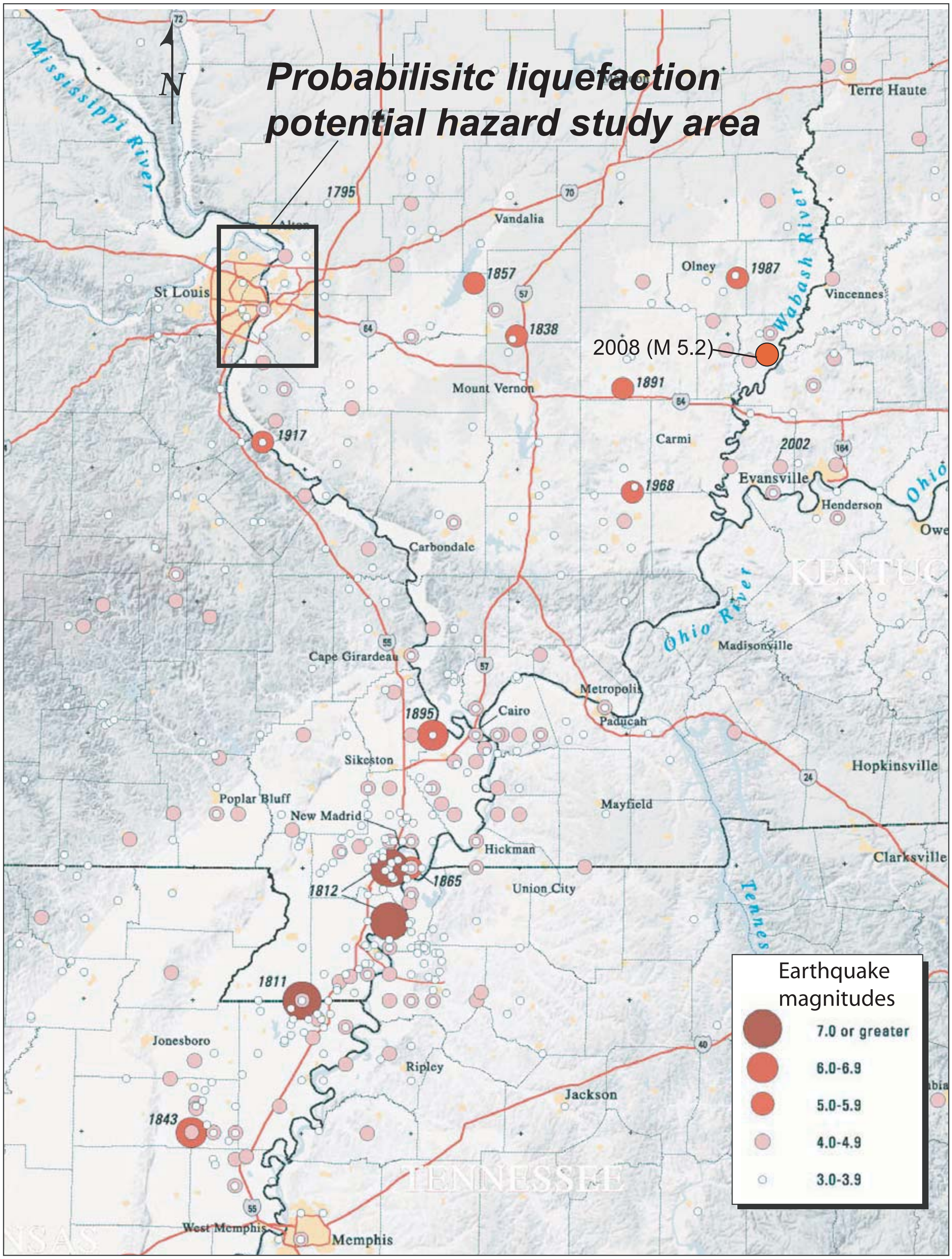

Figure 4. Regional seismicity map showing earthquakes from 1699 - 2002, with magnitudes above 3.0 (from Wheeler et al., 2002; USGS Map I-2812).

Specific deposit properties and existing conditions, and provides a more quantitative evaluation of liquefaction hazard.

Current liquefaction-related work in the St. Louis area focuses on refinement of ground motion estimates through detailed soil amplification assessment (Bauer, 2004), or developing cost-efficient in-situ soil tests via seismic piezocone penetration cone (Schneider and Mayne, 1999; Mayne 2001). The authors have completed liquefaction susceptibility mapping for five quadrangles within the St. Louis area (Pearce and Baldwin, 2005), however, to our knowledge, consistent and comprehensive quantitative probabilistic liquefaction potential hazard maps of the greater St. Louis metropolitan area have, to date, not been published.

2.2 Simplified Procedure

The Simplified Procedure is a method to estimate the liquefaction susceptibility of a deposit by relating standard penetration test (SPT) blow counts of a soil sample to earthquake-induced cyclic shear stresses, based on empirical liquefaction case history. This method is commonly employed because of the volume of SPT data that exists from public engineering projects (e.g. bridges, highways). This study primarily uses SPT data with lithologic descriptions from existing borehole collected within the field area. Other means exist to quantitatively estimate liquefaction susceptibility such as using shear wave velocity (e.g. Andrus and Stokoe, 1999), cone penetration resistance (e.g. Mayne, 2000, 2001; Rix, 2001, Tinsley et al., 1985) and Becker penetration test (Youd et al., 2001). For completeness, we examined the results from analyses that use alternative methods for assessing liquefaction susceptibility near, but not directly within, our study area (e.g. Mayne, 2001).

Because the Simplified Procedure has been extensively used and studied, the method has benefited from revisions and refinements that have improved the level of analysis overall (e.g. Seed et al., 1982, 1983, 1985; Robertson and Wride, 1987; Youd et al., 2001; Idriss and Boulanger, 2004). Most recently, Cetin et al. (2004) presented revisions to the Simplified Procedure that are based on updates to the case history database to include new field sites from recent liquefaction events (e.g. 1999 Kobe, Japan), a quality screening index for weighting the accuracy of reported case data, and a “Baysian” statistical analysis. The Baysian analysis performed by Cetin et al. (2004) reportedly results in empirical liquefaction relationships that have minimal bias and uncertainty as compared to the previous relationships (e.g. Youd et al., 2001). We use the recent relations developed by Cetin et al. (2004) in our liquefaction triggering threshold analysis of the deposits within St. Louis region. The estimated triggering threshold for liquefaction (i.e., susceptibility), expressed as percent gravity, is assigned to the corresponding surficial geologic map unit in the GIS database. The susceptibility maps are then intersected with the probabilistic ground motion and the trigger thresholds are analyzed with respect to PGA, thus developing a detailed hazard map of liquefaction potential.

3.0 REGIONAL GEOLOGY

The St. Louis region lies within the continental interior of the central United States, along the border of states of Illinois and Missouri; the large and oft-flooding Mississippi River delineates the boundary between the two. The Mississippi River is eroded into sedimentary rocks of Pennsylvanian and Mississippian age, and a wide mender belt results in an expansive low-lying alluvial floodplain that is flanked by bluffs of the higher standing "uplands". The study area was geologically influenced by at least two major Pleistocene glacial advances (Grimley, 2000). As a result of the glaciations, packages of till and sequences of loessal silts (e.g. Roxanna and Peoria) were deposited over areas of the St. Louis region. The more ubiquitous loessal silts are thickest proximal to the bluffs, and thin away from the bluffs and rivers (Goodfield, 1965). The silt deposits blanket nearly all of the uplands topography, and mantle some of the terrace remnants. In the upland areas, Pleistocene loess overlies Paleozoic carbonate and marine shale rocks (Harrison, 1997). The Paleozoic carbonates are known to be the source of karst dissolution (Hoffman, 1991), and typically is responsible for maintaining the generally steep bluffs of the upland rims. The upland areas are slightly to moderately dissected by smaller and larger creeks and streams that flow toward the Mississippi or Missouri Rivers; fluvial deposits and floodplain surfaces are associated with the drainages.

Inset to the uplands is a thick (up to 150 feet) package of granular alluvial valley fill that creates the expansive low-lying floodplain ("American Bottoms" in Illinois, "Columbia Bottoms" in Missouri). The Pleistocene river valley, containing higher energy streams, was carved down to pre-Cenozoic limestone bedrock in places (e.g. Chain of Rocks), and was subsequently backfilled by late Pleistocene coarse glacial outwash deposits (Henry Formation). The Pleistocene outwash is overlain by additional valley fill, consisting of about 60 feet of relatively finer-grained, intercalating Holocene alluvial sand (Cahokia Formation - sand facies) and overbank clays (Cahokia Formation - clay facies). The overall fining-upward sequence is interpreted to result from the change to a meandering, rather than braided, Mississippi River system during the Pleistocene-Holocene transition (Grimley and Lepley, 1999).

Remnants of Pleistocene fluvial terraces exist, most notably a slack water-environment clay 470- to 480-ft elevation that is believed to have been deposited as ice advanced across the Mississippi valley, temporarily damming it (Grimley, 2000; Goodfield, 1965). Fairly well-preserved terraces are present along the Meramec River near the confluence with the Mississippi River, and likely represent fluvial downcutting following the retreat of ice and incision of the floodplain. Other Pleistocene terraces, composed of coarse glacio-fluvial outwash sediment, were cut at lower elevations and exist marginal to the upland bluffs. Small streams and creeks emanate from atop the bluffs on both sides of the river, transporting sediment and water to the valley floor. Holocene alluvial fan deposits with relatively high silt content are present at the base of the bluffs. The broad valley floor is composed of young unconsolidated alluvium from meandering and flooding of the Mississippi and Missouri Rivers and to a lesser degree, minor tributary creeks and local alluvial fans.

The Mississippi River is known to have been very active in the late Holocene to Recent time, meandering across the wide floodplain, carving distinctive meander scrolls and abandoned channels on the modern floodplain. The following descriptions attest to the historical activity of the Mississippi River:

> *The river lost its narrow aspect at St. Louis after 1804 when a small sand bar formed near the Illinois shore near Bissell's Point. It deflected some of the river current against the east bank, causing a wash out and subsequent widening of the river* [to the east] *as well as the creation of Bloody Island from the sand bar. This trend continued until after 1850 when dykes were built to prevent the channel from completely deserting the St. Louis* [Mo.] *side of the river.* (City of St. Louis, 2004)

And,

> *The Illinois shore was covered by a wooded island, which had been washed away by 1830. The capricious action of the river had shifted to the Illinois side to such an extent by this time that sand bars had developed into Duncan's and Quarantine Islands in the river opposite the Soulard area. The formation of Duncan's Island threatened to block off the St. Louis levee from the river channel by 1845. This was prevented by the harbor works, started by Lt. Robert E. Lee, which caused the channel to again shift to the Missouri side and which later resulted in the washing away of the two islands.* (City of St. Louis, 2004)

These accounts illustrate the naturally meandering tendency of the Mississippi River over the last two centuries. This is an important process for depositing potentially liquefiable sediments (very young, unconsolidated alluvial deposits) on the floodplain. However, these accounts also document the beginning of major engineering modifications to the river system (e.g. levees). These modifications are designed to control flood flows and enhance barge-based shipping and navigation. Currently a system of levees, floodwalls, and canals are designed to protect urban areas against flooding damages or loss of real estate from lateral shifting of the river. However, these structures occasionally exceed capacity and fail to contain the water and sediment of the Mississippi River, as in some instances during 1993. Additionally, should the “doomsday” scenario occur (i.e., large earthquake during large flood), the resultant liquefaction of the foundation beneath the levees, or the levees themselves, may be subject to permanent deformation and possible structural failure, with associated catastrophic financial and personal damages.

4.0 REGIONAL SEISMICITY AND GROUND MOTION

The St. Louis region is characterized as experiencing relatively low magnitude earthquakes from diffuse sources that are not atypical of the central United States seismotectonic setting (Figure 4). However, the region is located near known active seismogenic source areas, such as the New Madrid seismic zone (NMSZ), the Wabash Valley seismic zone (WVSZ), and the Commerce geophysical lineament (CGL) that could potentially trigger liquefaction in the study area. The NMSZ (northern section) is about 170 miles (275 kilometers) south of the St. Louis region, and the WVSZ is about 150 miles (240 kilometers) east of the region. These sources are considered in Frankel et al (2002) that estimate ground motion across the nation, including the central US. For the purposes of this study, we consider peak ground motions as estimated by the USGS (Frankel et al., 2002) at the 2% and 10% exceedance in 50 years. The reader is referred to this report for detailed documentation regarding the development, application, and limitations of these data.

The north fault segment of the NMSZ (New Madrid North Fault) is believed to have produced a large magnitude earthquake during the 1811-1812 earthquake series, and although variable as a result of the estimating technique, the magnitudes (M_w) estimated range from 7.5 to 7.6 (Johnston, pers. comm., 2004), 7.2 to 7.5 (Bakun and Hopper, 2004), and 7.0 (Hough, 2004); a weighted mean average from five maximum magnitude estimates is 7.3 (M_w) (Geomatrix, 2004). The WVSZ is believed to have produced an earthquake 6,000 (+- 200) years before present, with an estimated range of maximum magnitudes **M** ~7.2 to 7.3, to possibly as high as **M** 7.5 to 7.8. (Geomatrix, 2004). These earthquakes occurred prior to modern seismological instrumentation; therefore, the magnitudes of the events are estimates based on paleo-liquefaction (e.g. Obermeier, 1989), paleo-seismologic investigations (e.g. Tuttle et al., 2002), MMI intensities, and interpretation of historical written accounts. Thus, while there is a fair amount of uncertainty regarding the details of the recurrence frequencies, magnitudes, and locations of major seismic events in the central US, the constraints by paleo-seismologic investigations suggest that the 10% in 50 year ground motion is a reasonably realistic scenario to evaluate, and the 2% in 50 year ground motion, while conservative, is not an unreasonable condition to evaluate because of the risk associated with the populated region.

This study uses the 2002 USGS National Seismic Hazard Maps (Frankel et al., 2002) of peak acceleration with 2% and 10% probability of exceedance. The national seismic hazard maps are the basis of seismic design maps in the International Building Code used in 47 states (Frankel, 2007). These maps both show a northeast-southwest trending ellipsoidal geometry of ground acceleration contours (as % g) centered on the NMSZ (Figure 5). The estimated accelerations rapidly diminish towards the St. Louis area for both exceedance probability scenarios, yet may be sufficient to initiate liquefaction depending on estimated triggering threshold. Ground motion and attenuation models are continuously refined and updated based on state-of-the-science (i.e., Frankel, et al 2007; Boore and Atkinson, 2006). However, the 2007 update to the national hazard maps is considered preliminary by the USGS, and therefore we employ probabilistic ground motion estimates from the 2002 hazard maps. Our work product exists as a GIS database that can be modified once the revised USGS input maps are prepared.

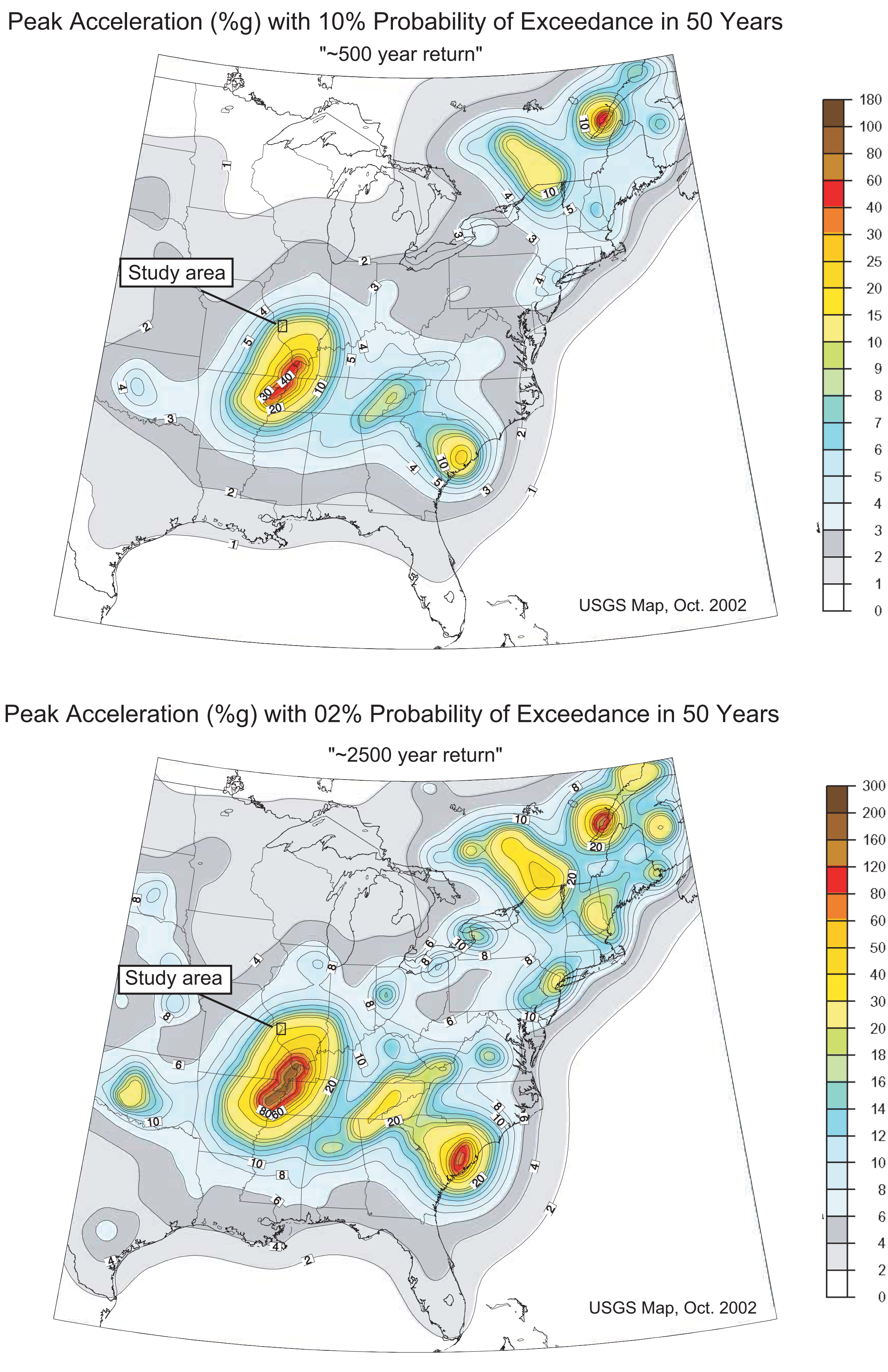

Figure 5. Probabilistic National Seismic Hazard Ground Motion Estimates (Frankel et al., 2002)

5.0 APPROACH AND METHODS

Development of probabilistic seismically-induced liquefaction potential hazard maps are based on the development of a comprehensive GIS database using subsurface borehole data for the St. Louis region and incorporation of advances in assessments of liquefaction susceptibility as previously described (Robertson and Wride, 1987; Youd et al., 2001; Cetin et al., 2004). While the details of the quantitative approaches vary slightly, in this study, we follow the general procedure accepted by California Geologic Survey (Knudson et al., 2000), and employed in previous liquefaction hazard projects such as in Boston, Massachusetts (Brankman and Baise, 2004), Simi Valley, California (Hitchcock et al., 1996; Hitchcock et al., 1999), and the San Juan, Puerto Rico area (Hengesh and Bachhuber, 1999). The liquefaction hazard mapping involves five main tasks:

1. Compile and evaluate existing geologic and geotechnical data;
2. Characterize ground water depths;
3. Estimate triggering liquefaction thresholds for granular geologic deposits;
4. Analyze probabilistic ground motion (PGA) values; and,
5. Evaluate liquefaction potential of geologic units based on 1, 2, 3, and 4.

Two probabilistic liquefaction potential maps are constructed at a scale of 1:24,000 on twelve quadrangles that contain deposits susceptible to liquefaction, resulting in twenty four quadrangle-scale maps (Figure 1). The methodology emphasizes the use of detailed Quaternary geologic mapping in conjunction with quantitative evaluation of subsurface information as a basis for estimating PGA triggering thresholds for liquefaction (Figures 2 and 3). A primary advantage of this approach is the categorization of borehole SPT data with respect to geologic map units which allows for the extension of data over areas where borehole coverage may be absent or lacking. Additionally, abundant subsurface data has been collected and provided to this study by the Illinois Department of Transportation and the Missouri Department of Transportation. This volume of data allows for an analysis of subsurface conditions within the greater St. Louis area. Supplemental data was provided by Army Corp of Engineers, St. Louis District.

5.1 Surficial Geologic Maps

In coordination with the Illinois State Geologic Survey (ISGS), we incorporated Quaternary surficial geologic maps developed by ISGS (see Section 6.1) for portions of nine 7.5-minute quadrangles that lie within Illinois borders and in our study area. We developed 1:24,000 scale Quaternary geologic maps for those portions of the quadrangles that lie within Missouri (Figure 1). This study incorporates the maps produced by ISGS as they represent the most-recent and most-detailed source of existing and available surficial geologic maps within the Illinois portion of the study area. This study benefited greatly from the integration of these map data.

The ISGS digital GIS maps depict Quaternary surficial deposits and are based on interpretation of soil maps, digital air photos, and field reconnaissance (Grimley, personal comm.). The surficial materials units delineated on the ISGS Quaternary geologic maps are assigned to relative age ranges (e.g. Wisconsin; about 75,000-12,000 years ago), and are associated with an interpreted depositional environment (e.g. abandoned channel). These criteria are consistent, in part, with our geologic mapping criteria, thus we believe the maps are suitable for use in liquefaction susceptibility mapping. The Quaternary geologic maps were constructed in a manner consistent with established criteria for use in liquefaction hazard mapping (e.g. Knudsen et al., 1997; Hitchcock and Wills, 1998; WLA, 1999; Hitchcock and Wills, 2000; Kelson et al., 2001) and is consistent with existing regional (i.e., 1:125,000-scale) maps of Missouri (Goodfield, 1965; Hoffman, 1995; Harrison, 1997). Criteria for delineating Quaternary deposits include:

(1) topographic position in a sequence of inset deposits or surfaces; (2) relative ages of individual deposits; (3) inferred depositional environment; and (4) continuity and lateral correlation with other stratigraphic units.

The ISGS Quaternary geologic maps and the Quaternary geologic maps developed in this study are similar to each other in their delineation of deposits except for the low lying alluvial floodplain areas. Our geologic mapping of the late Holocene alluvial map units are based on fluvial geomorphic frameworks of Kelson et al. (2001), Pearce and Kelson (2003), and Pearce and Baldwin (2004, 2005) and differentiates map units in detail based on inferred depositional environment and process (e.g. point bars, natural levees), topographic expression, and cross-cutting relationships. The delineation of these map units serve to provide additional detail to the Quaternary geologic map, and adds value to the analysis.

ISGS mapping categorizes Holocene floodplain alluvium as one overall formation (Cahokia Formation) with two informal members: a sand facies member and a clay facies member. Because of this existing framework, we needed to provide a context for associating our detailed Holocene map unit classifications to the ISGS map units, in order to have a consistent stratigraphic framework for evaluating and mapping the liquefaction hazard in the St. Louis region. The proposed map unit association framework was developed on the basis of similar interpreted environments of deposition, because this is one of the key geologic criteria for assessing liquefaction (e.g. Youd and Perkins, 1978). The presentation and justification for this framework is discussed in Section 6.0.

The geologic and liquefaction hazard maps were constructed in a GIS-environment at 1:24,000-scale. The use or display of the maps at scales greater than 1:24,000 is neither appropriate nor recommended, and will violate the spatial resolution of the map. Enlargement of the maps will incorrectly imply undue accuracy of the map and the susceptibility analysis. These maps should not be considered as substitute for a site specific study.

5.2 Liquefaction Susceptibility Calculations

The twelve quadrangles chosen for investigation in this study were selected on the basis of the concentration of industrial and commercial development and lifelines, the presence of unconsolidated granular sediments, and the availability of geologic and geotechnical data. This research updates and refines previous PGA trigger and susceptibility estimates for the St. Louis area (Pearce and Baldwin, 2004; Pearce and Baldwin, 2005), based on an expanded data set. The final liquefaction susceptibility maps integrate existing subsurface data, surficial geologic mapping, and depth to groundwater to estimate triggering peak acceleration thresholds (PGA trigger). Our approach to assigning relative levels of liquefaction susceptibility based on estimated PGA trigger is shown in Figures 2 and 3. We analyzed the liquefaction susceptibility of surficial deposits in the St. Louis region on the basis of sediment texture, density, age, depositional environment, and groundwater conditions. These criteria govern the liquefaction resistance of a deposit (e.g. Youd and Perkins, 1987). Our quantitative analysis of liquefaction susceptibility of sediment is based on the Simplified Procedure of Seed and Idriss (1971) and subsequent revisions (Seed et al., 1983, 1985; Youd et al., 2001; Cetin et al., 2004), wherein the Standard Penetration Test (SPT) and other data (e.g. overburden, effective overburden, texture) provide a functional means estimating susceptibility to liquefaction (Figure 6).

Revisions to key coefficients of Youd et al. (2001) were introduced by Cetin et al. (2004). The revisions are based on (1) a re-screening of original and newly added empirical data quality and (2) a multi-dimensional Baysian statistical analysis of the impacts of the range in various susceptibility parameters and their effect on observed liquefaction resistance. The statistical analysis resulted in substantial changes in how the "non-linear shear mass participation" factor (r_d) is estimated. Cetin et al. (2004) assert that "robust" statistical analysis reduced inherent uncertainty in the liquefaction analysis, and that these new relationships are removed of inherent bias that existed in the earlier relationships. However, the premise of the deterministic Simplified Seed-Idriss approach remains the same with Cetin et al. (2004). We believe that because of the: (1) augmentation to the empirical liquefaction database, (2) data quality screening and ranking, (3) statistical analysis of the data, and (4) professional experience and judgment of the authors, that the revisions and updates are warranted and justified in their usage for liquefaction susceptibility analysis. Below is a summary of the implications of estimation of r_d on liquefaction analysis.

5.3 Soil Rigidity Factor (r_d)

This term is sometimes called different names (e.g. "soil rigidity factor", "non-linear shear mass participation factor", "stress reduction coefficient") but represents the same physical phenomenon: that a soil column experiences, and responds to, cyclic shearing forces in a vertically heterogeneous fashion, that varies non-linearly with depth. In simple terms, the soil column does not behave as an entirely rigid body when subjected to cyclic shear stresses caused by an earthquake. Because of this fact, calculated CSR must incorporate this term. Cetin et al. (2004) state the r_d is a function of several variables, however due to strong cross correlation among some parameters, there are four main descriptive variables: (1) depth (d), (2) earthquake moment magnitude (M_w), (3) intensity of shaking (a_{max}), and (4) site stiffness (V^*_s).

In summary, we used a revised Simplified Procedure approach incorporating Cetin et al. (2004) r_d factor (e.g. Seed and Idriss, 1971; Youd et al., 2001; Cetin et al., 2004), to quantitatively estimate the peak ground accelerations necessary to trigger liquefaction in a unit. We used the triggering PGA's for designated geologic units to develop relative susceptibility hazard rankings for the geologic materials for each geologic unit (Figures 2 and 3).

5.4 Probabilistic liquefaction potential calculations

The liquefaction susceptibility analysis serves as a foundation for probabilistic liquefaction potential analysis via PGA trigger estimates, and provides a consistent basis for quantitatively analyzing liquefaction potential hazard. The assessment of liquefaction potential for the St. Louis area utilizes the approach developed by Youd and Perkins (1987), which emphasizes the merging of liquefaction susceptibility mapping with probabilistic ground motion information. This is the current approach employed by the California Geologic Survey (CGS) in their liquefaction hazard zonation of communities in California (California State Mining and Geology Board, 1997). The probabilistic liquefaction potential hazard is a function of the estimated PGA values for a specified level of probability (i.e., 02% in 50 year, 10% in 50 year), and the estimated PGA trigger value. The probabilistic analysis calculates the difference between the PGA from the national seismic hazard maps (Frankel et al., 2002; Figure 5) and the geologic deposit's estimated liquefaction trigger value (i.e., susceptibility). Those geologic units where the probabilistic PGA is deficient of or exceeds the triggering threshold PGA are identified, and are ranked relative to each other as to their estimated liquefaction hazard potential. This research depicts the results of the liquefaction potential analysis as percent above or percent deficient of the PGA trigger threshold. In this way, we not only delineate areas above or below the liquefaction triggering threshold, but we provide a quantitative framework for understanding the distribution and magnitudes of exceedance or deficient.

6.0 DATA

Four key data are needed for successful evaluation of the probabilistic liquefaction potential of the Quaternary deposits: (1) Quaternary geologic maps, (2) subsurface borehole stratigraphic and geotechnical logs, (3) information on the regional depth-to-groundwater, and (4) probabilistic earthquake ground motion data. Quaternary geologic maps provide information on unit age and depositional environment. Subsurface logs are a source of information about the physical and technical properties of the units that are needed for the Simplified Procedure, such as blow counts, soil texture (e.g. USCS unit designation), fines content, and unit weights. Regional depth-to-groundwater is critical for calculating effective overburden stress in the Simplified Procedure, and is a sensitive control on liquefaction. Input parameters for the liquefaction calculations are also needed, such as shear wave velocity, unit weights, and percent fines contents, and are largely based on published reports or on reasonable estimates from subsurface borehole data. Below we describe the sources, rationale, and limitations of our data.

6.1 Quaternary Geologic Mapping

Quaternary geologic maps used in this study are from: (1) existing Illinois State Geologic Survey 1:24,000-scale mapping that covers areas in Illinois; and (2) newly developed 1:24,000-scale Quaternary geologic mapping that covers the Missouri portion of the study area quadrangles (Figure 1).

For quadrangles in Illinois, we integrated the following existing digital Illinois State Geologic Survey Quaternary geologic maps[1]:

1. Alton Quadrangle; Illinois Geologic Quadrangle Map; D.A. Grimley, 1999;
2. Bethalto Quadrangle; Illinois Geologic Quadrangle Map; D.A. Grimley, 2003 (originally STATEMAP, 2003)
3. Cahokia Quadrangle; A. Phillips, 1999;
4. Columbia Bottom Quadrangle; D. Grimley and S. Lepley, 2001;
5. French Village Quadrangle; Illinois Geologic Quadrangle Map; D.A. Grimley and E.D. McKay, 2004;
6. Granite City Quadrangle; STATEMAP, A. Phillips, D. Grimley, and S. Lepley, 2001;
7. Monk's Mound Quadrangle; Illinois Preliminary Geologic Map; D. Grimley, A. Phillips, and S. Lepley, 2007;
8. Oakville Quadrangle; STATEMAP, J.A. Devera, 2003;
9. Wood River Quadrangle; Illinois Preliminary Geologic Map; D.A. Grimley and S.W. Lepley, 2001.

For those portions of our study area that lie in Missouri, we developed new, 1:24,000-scale Quaternary geologic maps based on: (1) review of previous, regional geologic mapping (e.g. Goodfield, 1965; Schultz, 1993; Hoffman, 1995); (2) inspection and interpretation of stereo-paired black and white 1958 aerial photographs, review of historical geographic and topographic maps of the St. Louis area (e.g. Paul, 1844; Metropolitan Sewer District, 1899); (3) inspection of modern digital air photos, soils and topographic maps; (4) analysis of subsurface boring logs; and (5) field reconnaissance. The 1958 aerial photograph set was chosen because it provides the oldest highest quality, 1:24,000-scale, stereo-paired images available for the map area. This study completed mapping for parts or all of the following quadrangles: Alton, Cahokia, Clayton, Columbia Bottom, Granite City, Oakville, Florissant, and Webster Groves (Figure 1). Quaternary deposits were evaluated on the basis of: (1) topographic position in a sequence of inset deposits or surfaces; (2) relative ages of individual deposits; (3) relative degree of soil

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[1] http://www.isgs.uiuc.edu/

profile development; and (4) continuity and lateral correlation with other stratigraphic units. Below we describe the Quaternary geologic mapping and map units.

6.1.1 Quaternary Geologic Mapping Completed for this Study

The surficial geology in the St. Louis region is dominated by sediment that was deposited as a result of several repeated ice advances and retreats in the Quaternary. We recognize four primary aerially-extensive deposits, from oldest to youngest: late Pleistocene eolian loess material (as much as 40 feet thick) derived from various sources (e.g. Grimley, 2000; Goodfield, 1965), late Pleistocene coarse-grained glacio-fluvial valley train outwash (about 100 feet thick), Holocene fine- to medium-grained floodplain alluvium (about 50-60 feet thick), Holocene tributary alluvium (about 10-20 feet thick), and artificial fill (variable thickness (Plate 1).

The glacio-fluvial deposit is interpreted to be a relatively high-energy of deposition (e.g. braided stream) due to the coarse texture of the deposit, and the depositional proximity to the ice margin. The late Pleistocene outwash deposits are exposed at the surface as terrace remnants at or near the base of the bluffs along the Missouri and Mississippi River fronts. A majority of the glacio-fluvial unit is present in the subsurface now buried by younger alluvium.

During the Holocene, the Mississippi River evolved to a more meandering-type stream, with lower overall depositional energy as the ice retreated and discharge and sediment load characteristics changed. Lateral migration of the Mississippi and Missouri Rivers and relatively frequent overbank flooding characterizes the late Holocene fluvial system, with distinct sand-rich facies associated with the former channel and bar deposits (e.g. meander scrolls), and clay- and silt-rich facies associated with overbank deposition of fines (e.g. crevasse splays). These late Holocene deposits are mapped based on relative position, topographic expression, and inferred depositional environment. However, the subdivided fluvial units are difficult to differentiate in subsurface borehole logs due to the relatively sparse lithologic descriptions within the logs.

Artificial fill is somewhat less extensive, but is important because it is generally considered liquefiable when composed of heterogeneous material emplaced without employing modern engineering techniques (e.g., Holzer et al., 2002). The fill, therefore, is subject to the effects of strong ground shaking induced by earthquakes. We classify fill as either engineered or "non-engineered" based on estimated vintage of construction (e.g., pre- or post- circa 1960). This classification generally refers to the overall method and nature of emplacement technique. Engineered fill for roads tends to be designed for stability and therefore tends to be of suitable material for construction, and tends to be compacted to a calculated amount. This is usually, but not necessarily, the case for highway or Interstate embankments. We do not have engineering or borehole records that substantiate this interpretation and delineation. Therefore, our mapping of engineered artificial fill based on topographic expression and should be considered subjective, at best. As seen in subsurface boring logs, non-engineered fill is usually composed of a mixture of natural materials and foreign debris (bricks, glass, wood, ash). Typically, non-engineered fill is not compacted, and tends to have highly variable blow counts, suggesting vertical heterogeneity. We infer that this material was used to construct the artificial levees that exist on the floodplain, or as heterogeneous reclamation and fill material under urbanized areas. Generally, non-engineered artificial fill underlies populated areas (e.g. downtown St. Louis), and may or may not be locally liquefiable depending on site-specific conditions beyond our ability to differentiate, given the regional quadrangle-based mapping of this study.

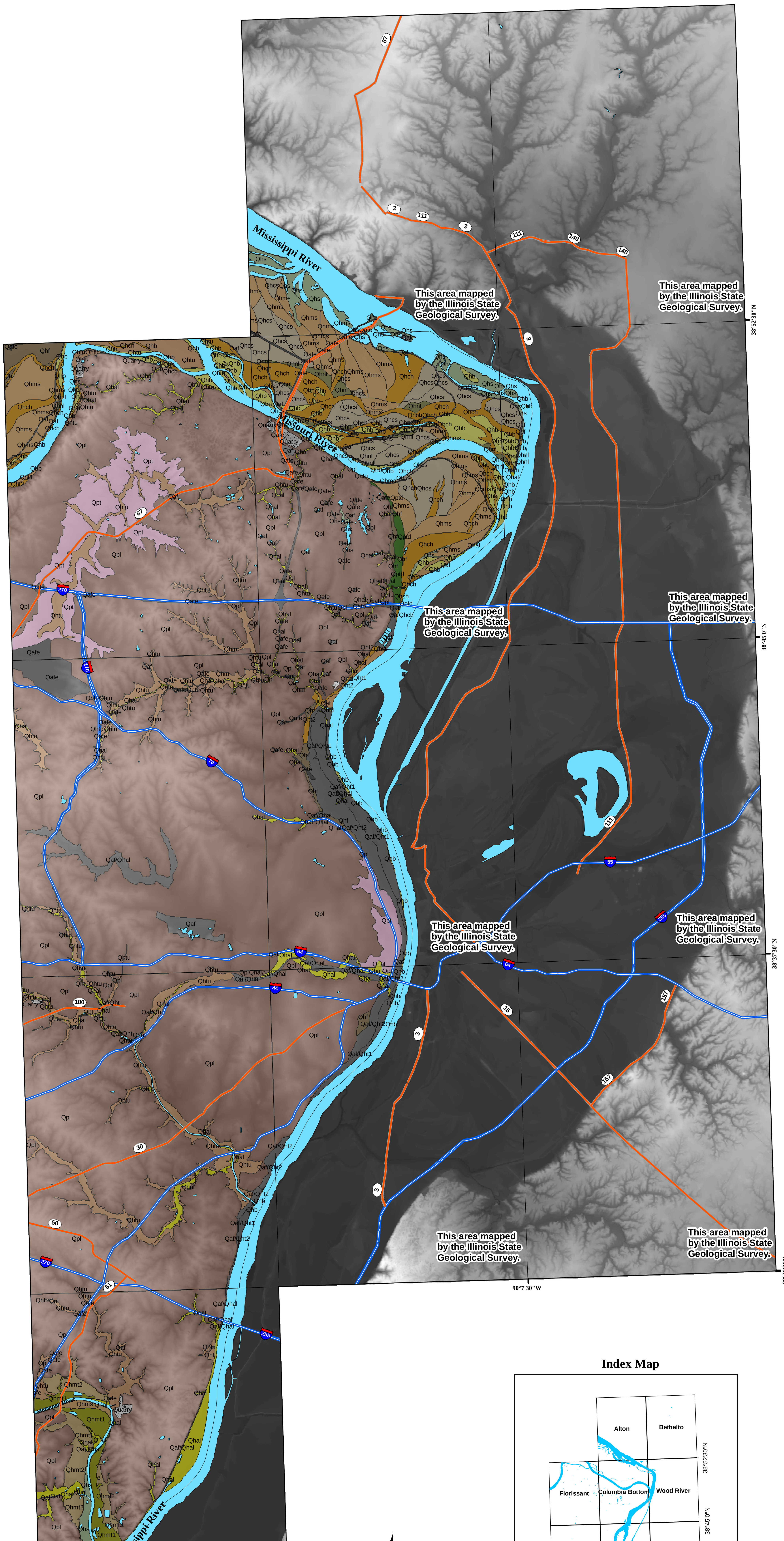
Quaternary geologic mapping in the area of the original settlement of St. Louis is difficult due to pre-aerial photography cultural modification. The settlement was established in late 1763 by Pierre Laclede Liguest, near present day Jefferson National Expansion Memorial Park. Historical maps, drawings, and reports document the original conditions, but can be difficult to reconstruct because referenced landmarks (e.g. buildings, street intersections) may no longer exist, or have been renamed or relocated. Very early maps commonly lack sufficient geographic control or accuracy to be used for other than illustrative purposes. Written reports commonly are unclear in the language, thus making interpretation and reconstruction of described landforms difficult. Early settlers used the bedrock that comprised the bluffs to the east as local quarries for house building stone (City of St. Louis, 2004), which degraded already gentle bluff slopes. A description of the original settlement site is described as:

> *Laclede and his band of traders landed at what is now the foot of Walnut Street* [in November, 1763]. *Here was a high limestone bluff rising about forty feet above the Mississippi, sloping back in two or three terraces to the west and extending about two miles along the riverfront. The bluff and the ceceding* [sic] *terraces were covered by a growth of timber extending irregularly west as far as present day Fourth Street…A small creek flowed into the river below the selected site, it traversed a wooded valley across the prairie from the east. Affording a place for the erection of a mill and dam, the creek later was called Mill Creek, and formed Cheauteau's Pond. Its valley marked the south edge of the bluff along the riverfront.* (History of St. Louis).

This description of the landscape is clearly different from that seen today. As described earlier, the activity of the Mississippi River in the 1800's was a general trend of lateral migration eastward. Upon examination and comparison of Paul's (1844) map and the modern topographic maps, it is apparent that the western boundary of the Mississippi River had substantially shifted eastward near Jefferson National Expansion Memorial Park, thus sub-aerially exposing the alluvial sediments, which were subsequently covered by artificial fill. We note that during the 1800's the Mississippi River migrated eastward, leading to deposits of large sand bars along the main channel (e.g. Duncan's Island). We infer that this shift in the river position exposed the alluvium (now a terrace), which was subsequently developed for the expanding town. We map this deposit as artificial fill (Qaf) over alluvium (Qht1), to depict the materials at the surface and the unconsolidated Quaternary deposits beneath.

Delineation of Quaternary terraces (map unit Qht) in the downtown area (Plate 1) is based largely on examination of 2-foot topographic contours (St. Louis Metro Sewer, 1899), modern topographic maps, relative geomorphic position adjacent to the river, and limited subsurface borehole data. It is possible that Qht1 and Qht2 may be a single alluvial deposit, rather than two distinct cut-and-fill deposits, with two surfaces cut on top as the Mississippi River meandered and slightly incised the deposit. We do not have sufficient subsurface geologic information across the two map units to compare the deposits. In the area of Riverview, and downtown St. Louis, historic and modern small creek channels (e.g. Mill Creek, Harlem Creek, and Maline Creek) emerge from the higher elevations to flow along, and across, the Qht1 and Qht2 terraces. Because the creek channels cross-cut the mapped terraces, they must therefore be younger than the terraces. Older floodplain deposits are present along major waterways within the upland area (e.g., River des Peres, Gravois Creek; Plate 1). Additionally, broad fluvial terrace surfaces are present along the Meramec River near the confluence with the Mississippi River. Relative topographic position and relative degree of surface dissection suggests that these abandoned floodplain deposits post-date latest Pleistocene loess deposition, but may represent early Holocene floodplain construction as the modern creeks are fairly incised into these deposits, suggesting sufficient time for downcutting. Lack of absolute age data precludes robust quantitative constraint of the age of these floodplain deposits.

Geologic maps by Goodfield (1965), Schultz (1993), and Hoffman (1995) depict extensive areas of (non-engineered) artificial fill that presumably overlies alluvial surfaces adjacent to the Mississippi River. Boring logs and subsurface soundings indicate that the non-engineered artificial fill is composed of a variety of materials such as cinders, bricks, wood, re-worked and locally sourced sand and silt, gravel and rubble. The geotechnical properties of these deposits, and their expected response to strong ground



N

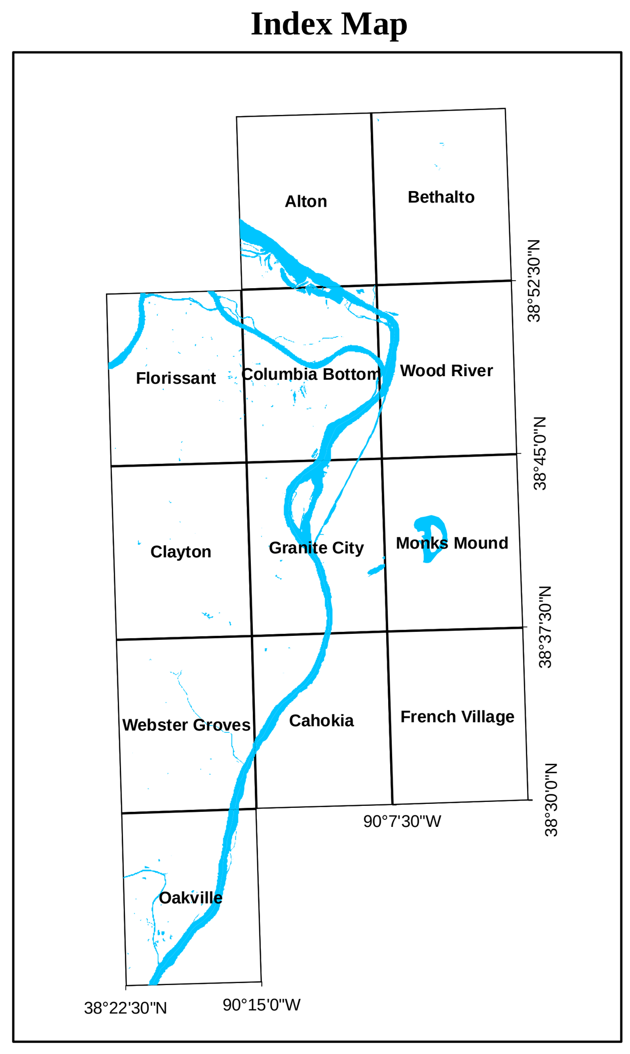
0 5 km

0 Scale: 1:96,000 3 mi

Explanation

Qafe	Qafe – Artificial fill (engineered) (Historical). Artificially emplaced mixture of native or imported soil material, loose to dense. This unit is mapped where alterations to natural topography can be observed (e.g. berms, interstate fill prisms). This unit is differentiated from Qaf on the assumption that it is generally, but not necessarily, machine compacted to a given dry density, although this is uncertain.	Latest Holocene (Historical)
Qaf	Qaf – Artificial fill (Historical). Artificially emplaced, clays, silts, sands, or gravel in various relative quantities, with or without a heterogeneous mixture of cinder, glass, brick, wood fragments, ash, "rubble". This unit has variable thickness and extent where it occurs in flat, urbanized areas adjacent to the Mississippi River.	
Qaf/Qhal	Qaf/Qhal – Artificial fill (Historical). Qaf emplaced over tributary alluvium deposit.	
Qaf/Qht	Qaf/Qht – Artificial fill (Historical). Qaf emplaced over terrace (Qht) deposit.	
Qaf/Qht1	Qaf/Qht1 – Artificial fill (Historical). Qaf emplaced over terrace (Qht1) deposit.	
Qaf/Qht2	Qaf/Qht2 – Artificial fill (Historical). Qaf emplaced over terrace (Qht2) deposit.	
Qhb	Qhb – Channel bar (Holocene). Fine to medium sand, silty sand to clayey sand, some intercalated clay layers, stratified, loose to medium dense. Alluvial deposit of the Mississippi and Missouri Rivers, constructed in the lateral or medial portion of the channel from bedload transport and accretionnary processes.	Holocene
Qhs	Qhs – Marsh or backswamp deposit (Holocene). Clays and silts, silty clay to clayey silt with minor sand component; massive to stratified; some organic detritus; soft to stiff. Alluvial deposit from slackwater conditions, typically occurring in relatively low topographic areas such as abandoned channels or swales between the bluffs and the natural levees of a floodplain.	
Qhnl	Qhnl – Natural levee deposit (Holocene). Sandy silts to clayey silt, with occasional fine sand lenses; soft to stiff. Alluvial deposit constructed from channel overbank events that results in the development of topographic ridges that are highest proximal to the channel bank, and are aligned parallel to the channel course.	
Qhcs	Qhcs – Crevessase splay (Holocene). Silty clay to clay, with minor very fine sand component; soft, vertically stratified. Alluvial overbank event occurring due to breaches or cracks (i.e. crevasses) in natural levee deposits.	
Qhch	Qhch – Channel (Holocene). Fine to medium sand, silty sand to clayey sand, with some granule and pebble content; typically well sorted; loose to dense. Alluvial deposit of the channel bed material.	
Qhms	Qhms – Meander scrolls (Holocene). Fine to medium sands, with some silt and clay layers; stiff, laterally and vertically sorted. Alluvial deposit constructed as a channel migrates, and the old position of a point bar is preserved topographically as an arcuate system of ridge and swales referred individually to as scroll bars.	
Qhal	Qhal – Tributary alluvium (Holocene). Fine to coarse sand, silty clay to slightly sandy clay, silt containing shells and roots; gray; loose. Alluvium from channels draining the uplands, tributary to the Mississippi and Missouri Rivers. The silt content is from locally re-worked and re-deposited loess.	
Qhmt1	Qhmt1 – Terrace (Holocene). Fine to medium sand with traces of gravel, and lenses of silty clay to clay; grey; stiff to medium dense. Alluvial deposit from Meramec River, exposed by abandonment and incision during post-glacial times.	
Qhmt2	Qhmt2 – Terrace (Holocene). Sandy silt, silt with fine sand lenses, fine sand, localized clay layers near the top of the section; tan; very loose to medium dense; poorly sorted. Alluvial deposit from Meramec River.	
Qht1	Qht1 –Terrace (Holocene). Fine to medium sand with traces of gravel, with lenses of silty clay to clay in the upper section; grey; stiff to medium dense. Limestone is at about 80 feet below ground surface, and is veneered by a thin gravel-cobble layer. Alluvial deposit from Mississippi River, exposed by abandonment and incision during post-glacial times, this surface is inset about 6 feet into Qt2.	
Qht2	Qht2 –Terrace (Holocene). Sandy silt, silt with fine sand lenses, fine sand, localized clay layers near the top of the section; tan; very loose to medium dense; poorly sorted. Alluvial deposit from Mississippi River. This unit overlies limestone bedrock, whose surface deepens toward the river (13' depth to 60' depth).	
Qhtu	Qhtu – Undifferentiated Terrace (Holocene). Sandy silt to silty clay; soft to stiff; stratified. Alluvial deposit from upland channels tributary to the Mississippi and Missouri Rivers.	
Qhf	Qhf – Alluvial fan (Holocene). Predominantly clayey silt, thin layers of fine to medium sand; gray to brown; soft. Alluviual deposit from distributary channels draining the uplands. The silt content is from locally re-worked and re-deposited loess.	
Qptd	Qptd – Deer Plain Terrace (Pleistocene). Fine to coarse sand with gravel lenses, fine sandy clay, clayey silt; brown to yellowish-brown; stratified; soft to stiff (Goodfield, 1965). Fluvial terrace deposited from glacial outwash, occurs as an isolated remnant along the bluffs near Columbia Bottom Road.	Pleistocene
Qpt	Qpt – Lacustrine Terrace (Pleistocene). Sandy clay to sandy silt, clay with some coarse sand; gray to brown; very soft to medium stiff. Lacustrine deposit created by damming of the Mississippi River from advancing ice (Goodfield, 1965).	
Qpl	Qpl – Peoria and Roxana Loess -undifferentiated (Pleistocene). Silty to clayey silt, tan to brown to pinkish-brown to yellowish -brown; usually massive; some limonite nodules and staining; terrestrial gastropods common (Grimley and Lepler, 1999).	
Water	Water.	
Quarry	Quarry - Excavation associated with gravel or bedrock extraction.	
Interstate Highway		
State Highway		

Index Map



Notes:
- All geologic contacts should be considered approximate.

-Base map is a color-by-elevation Data Elevation Model (DEM).

-The geologic map was constructed at 1:24,000 - scale.

-Enlargement of the map and use at greater scales can result in apparent inacurracies.

-The surficial geologic mapping on the Illinois side of the study area was performed by Illinois State Geological Survey (ISGS). http://www.isgs.uiuc.edu/

-This work was performed under the U.S. Geologic Survey's External Research National Earthquake Hazard Reduction Program **(NEHRP) Grant # 05 - HQGR-0063.**

-The views and conclusions contained in this document are those of the Principal Investigators and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Projection: UTM Zone 15 NAD 83

Probabilistic Liquefaction Potential St. Louis Area

Surficial Geologic Map for Missouri Portions of the Alton, Florissant, Columbia Bottom, Wood River, Clayton, Granite City, Wood Grove, Cahokia, and Oakville quadrangles.

WILLIAM LETTIS & ASSOCIATES, INC.

Plate 1

Authors: J. Pearce and J. Baldwin

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shaking, are essentially unknown, and are likely to be highly variable from one area to another due to the non-uniform manner of fill emplacement and source materials.

Engineered artificial fill deposits (Qafe) are interpreted from modern topographic maps as distinct alterations to the landscape contours (e.g. highway and railroad berms). We do not have information to directly assess the method of emplacement or characterize the material properties. Because these fill deposits were emplaced sometime after the 1950s and because they generally serve to support interstate travel loads, we assume that they were constructed using modern engineering principles (e.g. compaction), and will therefore behave differently than non-engineered fill. Additionally, we mapped artificial fill deposits that were presumably placed to create small ponds and lakes, and to allow for urban development (i.e. fill prisms for buildings). The composition of these fill materials is unknown. Thus, our interpretation and classification of engineered fill based on topographic map inspection may not necessarily reflect the actual conditions in the field, and should be viewed with caution. The delineation of artificial fill is consistent with mapping produced by ISGS (e.g. Grimley and Lepley, 2001) and mapping for liquefaction evaluations in the San Francisco Bay area (e.g. Knudsen et al., 1997), San Juan, Puerto Rico (Hengesh and Bachhuber, 1999), and Ventura County (Hitchcock, 1999).

Map Units for Quaternary Geologic Mapping in Missouri

The section describes the map unit symbols and generalized map unit lithologic descriptions. The descriptions, explanations, and interpretations of map are based on previous, smaller scale mapping (i.e., Goodfield, 1965; Hoffman, 1995), as well as our observations and interpretations from review of subsurface lithologic records. This mapping does not delineate the map category of "residuum", as this represents highly-weathered parent material and is post-depositional pedogenic feature rather than a Quaternary deposit, and is likely mantled, at least in our area, by a veneer of loess (i.e., Goodfield, 1965). The map units and symbols used in this study have not been formally adopted by the Missouri Department of Natural Resources and thus, should be considered proposed, but informal. Below we briefly describe the map units within Missouri portions of the study area, from oldest to youngest, as follows:

- Qpmc – Mill Creek Till (Pleistocene). Not exposed at surface, locally present in the subsurface. Sand and gravel with cobbles, clay, and silt in various proportions, minor to occasional lignite; brown to gray; very stiff. Glacial till and ice marginal sediments, occurs primarily as an aerially restricted deposit in the subsurface.

- Qpt – Lacustrine Terrace (Pleistocene). Sandy clay to sandy silt, clay with some coarse sand; gray to brown; very soft to medium stiff. Lacustrine deposit created by damming of the Mississippi River from advancing ice (Goodfield, 1965).

- Qptd – Deer Plain Terrace (Pleistocene). Fine to coarse sand with gravel lenses, fine sandy clay, clayey silt; brown to yellowish-brown; stratified; soft to stiff (Goodfield, 1965). Fluvial terrace deposited from glacial outwash, occurs as isolated remnants along the base of the bluffs.

- Qpl – Peoria and Roxana Loess -undifferentiated (Pleistocene). Silty to clayey silt, tan to brown to pinkish-brown to yellowish-brown; usually massive; some limonite nodules and staining; terrestrial gastropods common (Grimley and Lepler, 1999).

- Qht2 –Terrace (Holocene). Sandy silt, silt with fine sand lenses, fine sand, localized clay layers near the top of the section; tan; very loose to medium dense; poorly sorted. Alluvial deposit from Mississippi River. This unit overlies limestone bedrock, whose surface deepens toward the river (13' depth to 60' depth).

- Qht1 –Terrace (Holocene). Fine to medium sand with traces of gravel, with lenses of silty clay to clay in the upper section; grey; stiff to medium dense. Limestone is at about 80 feet below ground surface, and is veneered by a thin gravel-cobble layer. Alluvial deposit from Mississippi River, exposed by abandonment and incision during post-glacial times, this surface is inset about 6 feet into Qt2.

- Qhtu – Undifferentiated Terrace (Holocene). Sandy silt to silty clay; soft to stiff; stratified. Alluvial deposit from upland channels tributary to the Mississippi and Missouri Rivers.

- Qhf – Alluvial fan (Holocene). Predominantly clayey silt, thin layers of fine to medium sand; gray to brown; soft. Alluviual deposit from distributary channels draining the uplands. The silt content is from locally re-worked and re-deposited loess.

- Qhb – Channel bar (Holocene). Fine to medium sand, silty sand to clayey sand, some intercalated clay layers, stratified, loose to medium dense. Alluvial deposit of the Mississippi and Missouri Rivers, constructed in the lateral or medial portion of the channel from bedload transport and accretionary processes.

- Qhs – Marsh or backswamp deposit (Holocene). Clays and silts, silty clay to clayey silt with minor sand component; massive to stratified; some organic detritus; soft to stiff. Alluvial deposit from slackwater conditions, typically occurring in relatively low topographic areas such as abandoned channels or swales between the bluffs and the natural levees of a floodplain.

- Qhnl – Natural levee deposit (Holocene). Sandy silts to clayey silt, with occasional fine sand lenses; soft to stiff. Alluvial deposit constructed from channel overbank events that results in the development of topographic ridges that are highest proximal to the channel bank, and are aligned parallel to the channel course.

- Qhcs – Crevessase splay (Holocene). Silty clay to clay, with minor very fine sand component; soft, vertically stratified. Alluvial overbank event occurring due to breaches or cracks (i.e. crevasses) in natural levee deposits.

- Qhms – Meander scrolls (Holocene). Fine to medium sands, with some silt and clay layers; stiff, laterally and vertically sorted. Alluvial deposit constructed as a channel migrates, and the old position of a point bar is preserved topographically as an arcuate system of ridge and swales referred individually to as scroll bars.

- Qhch – Channel (Holocene). Fine to medium sand, silty sand to clayey sand, with some granule and pebble content; typically well sorted; loose to dense. Alluvial deposit of the channel bed material.

- Qhal – Tributary alluvium (Holocene). Silty sand, fine to coarse sand, silty clay to slightly sandy clay, and silt containing shells and roots; gray; loose. Alluvium from channels draining the uplands, tributary to the Mississippi and Missouri Rivers. The silt content is from locally re-worked and re-deposited loess.

- Qaf – Artificial fill. Artificially emplaced, clays, silts, sands, or gravel in various relative quantities, with or without a heterogeneous mixture of cinder, glass, brick, wood fragments, ash, "rubble". This unit has variable thickness and extent where it occurs in flat, urbanized areas adjacent to the Mississippi River. This unit also represents deposits composing the levees that are constructed on the floodplain between the Mississippi and Missouri Rivers, and on the Columbia Bottom wildlife refuge area.

- Qafe – Engineered artificial fill. Artificially emplaced mixture of native or imported soil material, loose to dense. This unit is mapped where alterations to natural topography can be observed (e.g. berms, interstate fill prisms). This unit is differentiated from Qaf on the assumption that it is generally, but not necessarily, machine compacted to a given dry density, although this is uncertain.

6.1.2 Illinois State Geologic Survey (ISGS) Quaternary Mapping

The reader is referred to the original reports and documentation for each quadrangle for a detailed explanation of the map criteria, map units, and Quaternary depositional history of the mapped quadrangles (e.g. Philips, 1999; Phillips et al., 2001; Grimley et al., 2001, and Grimley and Lepley 2001a, 2001b): The descriptions, explanations, and interpretations of map units for the ISGS quadrangles are as written for the Wood River quadrangle (Grimley and Lepley; 2001b). We used the ISGS map unit descriptions to develop our stratigraphic framework for the correlation of the final liquefaction susceptibility and potential maps; therefore we briefly describe the ISGS map units for Illinois as:

- Qd – Disturbed ground (Holocene). Artificially emplaced fill or removed earth; sediment of various types. Includes man-made materials in major highways, landfills, sand and gravel pits, and levee fills.

- Qcu – Cahokia Formation, upland facies (Holocene). Silt loam with some silty clay and sand, occasional gravel; gray to brown, may contain organic or man made debris. Alluvium from channels tributary to the main valley. Contains significant eroded and re-deposited loess material.

- Qcf – Cahokia Formation, fan facies (Holocene). Silt loam with occasional thin sand beds; brown, weakly stratified, and soft. Alluvium deposited by distributary channels; includes much re-deposited loess, and some deposits from interpreted mud flow events.

- Qcc – Cahokia Formation, clayey Mississippi Valley facies (Holocene). Silty clay loam, silty clay, and silt with occasional fine sand lenses; gray to brown, some thin red lenses, massive to well-stratified, soft to stiff. Abandoned channel fill and backswamp alluvium deposited in the floodplain of the Mississippi River.

- Qcs – Cahokia Formation, sandy Mississippi Valley facies (Holocene). Very fine, fine, and medium sand, with some coarse sand and gravel and some silt and clay layers; light brown to gray, stratified, loose to soft. Point bar and channel alluvium of the Mississippi River. This unit can be difficult to distinguish from Henry Formation (Qh) in subsurface logs. Generally recognized by relatively finer grain sizes, lower blow counts, and shallower depths.

- Qce – Cahokia or Equality Formation, undifferentiated (Pleistocene to Holocene). Silty clay to silt with some fine sand; gray to brown, massive to stratified, stiff. Fine-grained alluvium and/or lake deposits found at the east edge of the floodplain, deposited by Mississippi River backflooding.

- Qe – Equality Formation (Pleistocene). Silty Clay to silt with some fine sand; gray to brown to pinkish-brown, massive to stratified, stiff. Lake deposits laid down by backflooding of the Mississippi River during glacial episodes.

- Qh – Henry Formation (Pleistocene). Medium to coarse sand with gravel and some fine sand; fine sand where exposed near surface; light brown to gray. Glacial outwash deposits of the Mississippi River that are primarily buried by post-glacial Cahokia alluvium. Occurs as terrace remnants at the edge of the valley floor. This unit can be difficult to distinguish from sandy Cahokia alluvium in subsurface logs. It is generally recognized by relatively coarser grain sizes (medium sand to gravel), abruptly higher blow counts (e.g. ≥ 50), and deeper encountered depths.

- Qpr – Peoria and Roxanna Silts (Pleistocene). Silt to silt loam; yellow-brown to gray to pinkish brown; massive with some dark organic layers, friable. Loess deposited during glacial times. Preserved mainly in the topographically high-standing areas.

- Qg – Glasford Formation (Pleistocene). Pebbly silt loam to loam diamicton with common sand and silt bodies; olive to gray; weathered brown in the upper sections; typically massive and dense. Till and ice-marginal sediment. Occurs primarily in the subsurface, with few map exposures.

6.1.3 Correlation of Map Units

Because the Quaternary geologic classification framework used for mapping deposits differs across the state boundary, the map units were correlated for internal consistency during the liquefaction susceptibility analysis to provide a unified and logical analytical framework. The correlation of stratigraphic map units across the study area is shown in Table 1. This proposed stratigraphic correlation is primarily based on similar-interpreted depositional environment of each map unit. The ISGS maps three geologic deposits on the study area low-lying floodplain: (1) Cahokia alluvium (sand facies), (2) Cahokia alluvium (clay facies), and (3) artificial fill. We synthesized our map units, as appropriate, with reference to modern soil surveys, to conform to the more-generalized classification scheme used by ISGS. For instance, clayey Cahokia facies are interpreted to have been deposited by overbank or slackwater processes. Thus, we aggregate natural levee and crevasse splay deposits in this category. Also aggregated into this category are marsh (backswamp) deposits because of the finer grain sizes of the deposit, and the inferred relatively low energy depositional environment. This proposed stratigraphic correlation is reasonable because: (1) the generalized stratigraphic scheme of ISGS encapsulates our more detailed geologic units; and (2) the ISGS mapping scheme implies a depositional environment that also is captured by our mapping.

Table 1. Stratigraphic Correlation of Map Units

Unit Symbol (This study)	Map Unit (This study)	ISGS Unit Symbol	Classification	Relative Age
Qhaf	Artificial fill	AF	Disturbed ground	Recent
Qhafe	Artificial fill (engineered)			
Qhs	Marshes (backswamp)	Qcc	Cahokia Formation (clayey)	Holocene
Qhcs	Crevasse splay			
Qhnl	Natural levee			
Qhb	Channel bars	Qcs	Cahokia Formation (sandy)	
Qhch	Abandoned channels			
Qhms	Meander scrolls			
Qht1,Qht2,Qhtu	Fluvial terraces			
Qhmt1,Qhmt2	Fluvial terraces of the Meramec River*			
Qhal	Tributary alluvium	Qcu	Cahokia Formation (upland)	
Qhf	Alluvial fans	Qcf	Cahokia Formation (fan)	
Qpt3	Lacustrine terrace	Qe	Equality Formation	Pleistocene
Qptd	Deer Plain terrace	Qh	Henry Formation	
Qpl	Loess	Qpr	Loess	

6.2 Subsurface Boreholes

Subsurface borehole information used in this study was collected from various sources in differing formats. The bulk of our SPT data was provided by the ISGS and MoDOT databases compiling data from bridge and highway structures on the alluvial floodplain and some of the adjacent upland areas. The spatial location provided for each borehole is as accurate as possible (D. Grimley, pers. comm.); however, some original hardcopy records only included location information at Township, Range, and Section resolution (e.g. no quarter section resolution). Because of this fact, instances occur where multiple boreholes are plotted at the same spatial coordinate (e.g. the center of the Section). A lesser amount, but equally critical, subsurface data were obtained from Army Corps of Engineers, St. Louis District and plotted based on location maps provided with the core logs.

We also obtained subsurface geologic and geotechnical subsurface information from the Missouri Department of Transportation (MoDOT). Data was photocopied from the Log of Test Borings (LOTBs). These data are primarily located along major interstates, highways, and overpasses. Data included SPT results and shallow auger or push core soundings. Recent LOTBs include grain size distribution analysis and Atterberg limits for finer-grained samples. The boreholes were plotted by highway structure via GIS database. If the LOTBs were referenced to the MoDOT stationing coordinate system, we plotted the boreholes based on the description of the location on the log header, and by relative distance along station. We estimate these hand plots to be accurate within about 250 to 500 feet.

Reports and data were collected from various environmental investigation/remediation sites near the Mississippi River edge in Missouri (e.g. URS, 2001; Burns and McDonnell, 1994; Bechtel, 1990; IT Corporation, 2002). These data include limited SPT data, and generally are sounding and groundwater monitoring well information. Most of the SPT data from environmental sites are shallow (e.g. 20 to 30 feet), and predominantly encounter only artificial fill deposits. No information is included with these logs to estimate either the fines content of the fill, overall USCS classification, or unit weight. Therefore, this reduced the number of SPT samples we could quantitatively include from this data source.

We obtained additional subsurface stratigraphic information from the Army Corps of Engineers, St. Louis District, for portions of the downtown St. Louis floodwall in Missouri, and for a portion of the levee at the Chain of Rocks Canal. Both data sets lacked SPT information, but were used to assess the character and extent of the underlying subsurface deposits and stratigraphy. The stratigraphic data from the floodwall soundings were plotted on our map based on engineering-scale general plan and profile diagrams.

In areas of relatively sparse geotechnical data, the subsurface SPT data is correlated to a surficial geologic map unit (e.g. Knudsen et al., 1997; Hitchcock and Wills, 1998). In this way, the results of the Simplified Procedure can be extended to represent those geologic map units that lack subsurface borehole information. Because we have developed a stratigraphic correlation between units in Illinois with units in Missouri (Table 1), we rely on the results of the borehole analysis from Illinois deposits to infer susceptibility for similar mapped deposits in Missouri where subsurface data is sparse.

6.3 Groundwater

Depth-to-groundwater (DTW) is an important variable in the liquefaction evaluation, because it is controls effective normal stress exerted on a given sample. A worst-case scenario would set the DTW as zero, creating fully saturated conditions but, in our opinion, is a rare condition. A “doomsday” analysis would use fully saturated conditions. Commonly, DTW varies daily, seasonally, and annually; as well as vary locally and regionally. However, this study evaluates liquefaction susceptibility and potential based on “baseline” DTW conditions. That is, the DTW that would reasonably be expected based on regional topographic and hydrologic conditions and modern aquifer pumping activity. We constructed a scenario DTW map for the study area (i.e., Pearce and Baldwin, 2005), based on a synthesis of published maps and reports (Kolhase, 1987, Shicht and Buck, 1995), groundwater well data, and encountered free water levels in borehole logs. The reasoning for the scenario DTW map is described below.

6.3.1 Illinois DTW

Depth-to-groundwater (DTW) for potentially liquefiable sediments in Illinois was derived from the potentiometric surface map from Kohlhase (1987). This map shows the approximate elevation of the potentiometric surface from November, 1985, and clearly demonstrates the presence of drawdown cones. These cones have persisted in time and space (e.g. Collins and Richards, 1986; Schicht and Buck, 1995), as a result of ground water pumping for industrial usage and public consumption. Schicht and Buck (1995) show that groundwater pumping has decreased though time since its peak of nearly 110 mgd in 1956, compared to an estimated 58 mgd in 1990. They also show that groundwater elevations recovered somewhat as a result of the reduction in pumpage. Overall, the Kohlhase report (1987) estimates a higher potentiometric surface elevation than recently measured in 1990. This is partly due to higher stage elevations of the Mississippi River in November of 1990 compared to November 1985. We believe it is appropriate to use the highest historical groundwater elevations of Kohlhase (1987) for liquefaction susceptibility evaluation, because this provides a “conservative” (e.g. more susceptible) estimate of the hazard (e.g. Hitchcock et al., 1999, 2000; Knudsen et al., 2000). Additionally, we believe that the groundwater pumping from the Illinois aquifer sediments will continue to persist due to industrial and public needs; therefore the Kohlhase (1987) map represents relatively realistic present-day conditions. As a simplification, we assume that the potentiometric surface map from Kohlhase (1987) represents unconfined water table elevations, even though the aquifer is considered mostly a leaky confined aquifer.

This results in a slightly conservative analysis, since the potentiometric surface is generally above, or equal to, the water table.

We digitized the Kohlhase (1987) potentiometric surface map, and assigned elevation attribute values to the contour lines. We converted the groundwater surface elevations to depth-to-groundwater (DTW) values, by intersecting the digitized groundwater contours with digital land elevation data (10-meter cell size). Subtracting land surface elevation from potentiometric surface elevation yields a DTW value at each intersection point. These DTW data points were interpolated and used to construct DTW map with ten-foot contours (Pearce and Baldwin, 2005). This process for deriving depth-to-groundwater provides an estimated value only. The sources of uncertainty that contribute to possible error in our data include (1) the interpolation of the original potentiometric map, (2) the interpolation of the source land surface elevation file (up to 2 meters), and (3) the interpolation used in the creation of the DTW map (e.g. using land surface elevation instead of top of casing). Because of the annually and seasonally changing groundwater level, we consider this map a "scenario" condition, recognizing that other DTW conditions could be present at any given point and time.

6.3.2 Missouri DTW

Depth-to-groundwater data for the Missouri portion of the study area were compiled from three different sources: (1) USGS national well station data, (2) Missouri GSRAD digital information base (MEGA), and (3) boring logs if groundwater was encountered during drilling (but may not represent "recovered" conditions). The limitation with using these data for constructing a scenario DTW map is that the groundwater levels were recorded in different years for each well or boring, and also at different seasons of the year, and is therefore not temporally consistent as is with Kohlhase (1987). We constructed DTW contours for the alluvial areas based on review of the well data and reasonable hydro-geologic assumptions. We assigned the low-lying floodplain areas a DTW range of 0-10 feet. Our field reconnaissance in the Columbia Bottom Conservation area (April 2004) confirmed nearly saturated soil conditions. For urbanized areas generally topographically above the broad floodplain, we assigned a DTW value of 11-20 feet (Pearce and Baldwin, 2005). This is a reasonable estimate based on encountered free water in boreholes and groundwater elevation maps in environmental reports. Groundwater aquifers in the uplands are generally restricted to the Paleozoic carbonate basement rocks and local alluvium connected with present-day creeks. Groundwater level data in the higher-elevation loess-covered uplands area is scattered and sparse, at best. In the uplands area, DTW is extremely variable, but is on the order 60 feet below ground surface. However, the limited well data indicate that while DTW can exceed 100 feet, it only rarely is less than 40 feet. We characterize the upland loess areas as having DTW of greater than 40 feet, and we apply a somewhat conservative DTW of 10 feet for the upland tributary alluvium.

6.4 Shear Wave Velocity

Shear wave velocity is a variable that is used in the calculation of the coefficient r_d for the Simplified Procedure. We used shear wave velocities for our geologic map units based primarily on values obtained by B. Bauer (ISGS), cited in Hermann and Akinci, (2004), and to a lesser degree Pugin et al. (2002), Mayne et al. (2002), Atkison and Beresnev (2002), and MoDOT (2004). It should be noted that the values used in this study are estimates based on averages that represent a wide range of values in the soil column. Generally, for unconsolidated sediments, as the average shear wave velocity of a unit increases, the resistance of that unit to liquefaction decreases. Using values from the higher bound of a velocity range would produce a more conservative result (higher apparent liquefaction hazard).

For the liquefaction calculations, we largely used the values listed in Hermann and Akinci (2004) because: (1) those data are specific to our geologic units of interest, and (2) they are within the range of values determined by other investigators working in the same or similar geologic units (Table 2). We used the University of Missouri-Rolla (2004) velocity data for Artificial Fill units. As a note, Atkinson and Beresnev (2002) cite higher shear wave velocities for alluvium near Memphis as compared to St. Louis, which could represent a fundamental property that controls causes different site response to strong ground shaking (e.g. liquefaction). The shear wave velocities in Table 2 correspond with NEHRP soil class D.

Table 2. Estimated Shear Wave Velocities

	Estimated shear wave velocity (m s^{-1})				
Geologic Formation	**Hermann and Akinci (2004)**	**Pugin et al. (2002)**	**Mayne et al. (2002) †**	**UMR (2004)**	**Used**
Artificial fill*	x	x	x	215-245	230
Clayey Cahokia	200-230*‡	150-200*‡	150-200*‡	~180	200
Sandy Cahokia			220	~230	230
Upland Cahokia	x	x	x	x	200
Fan Cahokia	x	x	x	x	200
Henry Formation	200	x	x	x	230
Equality Formation	175	x	x	x	175
Loess	200	x	x	x	200
Till	365	x	x	x	365

† Tested Meramec River alluvium, ‡ values increase with depth, * undifferentiated units, “x” is no data

7.0 RESULTS

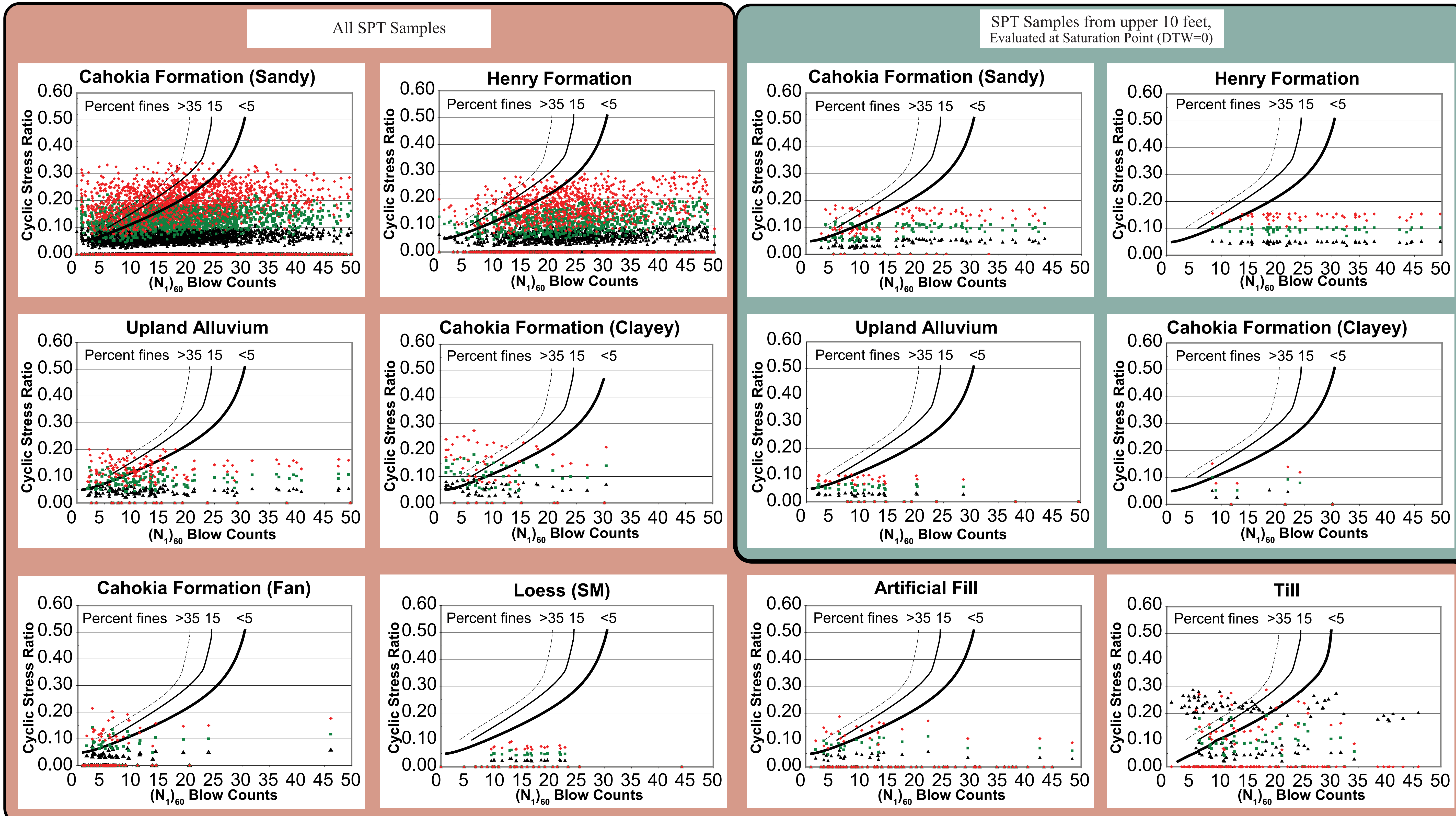
7.1 Susceptibility and PGA Trigger Estimates

This study analyzed nearly 11,700 SPT samples from over 450 boreholes that were drilled in the St. Louis region, to assess the texture and relative density of the Quaternary subsurface deposits. These data allowed a subsurface sampling of the stratigraphic units that compose the bulk of the valley alluvial fill. Each soil sample with SPT blow count data was assigned to a geologic map unit category to group the data for the liquefaction analysis. The Simplified Procedure shows the relationship between cyclic stress ratio (CSR) and SPT $(N_1)_{60}$ value for each map unit. Each plot shows the SPT $(N_1)_{60}$ against the expected cyclic stress ratio (CSR) with liquefaction threshold curves (Figure 6). We used 0.10g, 0.20g, and 0.30g as scenario values for maximum ground acceleration in the St. Louis region (a_{max}) for the susceptibility and PGA trigger analysis (Figure 6). Peak ground acceleration values needed to trigger liquefaction of a map unit are estimated by inspection of the plotted ($(N_1)_{60}$, CSR) pairs, in relationship to the triggering threshold curve. The population plots resulting from the Simplified-Procedure borehole analysis, in conjunction with geologic knowledge of the map unit's age (aging effects) and depositional environment (texture and relative density), lead to the estimated PGA trigger and susceptibility rating values.

This study updates and revises our earlier estimated liquefaction susceptibility values (Pearce and Baldwin, 2005), primarily based on incorporation of additional geotechnical data. Overall, our estimated triggering values have not substantially changed in magnitude, but the have changed in direction. That is, analysis of additional data has, in some instances, reduced the estimated susceptibilities of the map units by about 11 percent. We stress that the estimated triggering values are approximations based on the behavior of the entire population of data within each map unit, and generalize the susceptibility of the geologic deposits. The analysis shows, in general, that there is more variability of susceptibility within a given map unit than there is across all map units. Because of this, there will likely be site-specific instances where the actual liquefaction susceptibility may be greater or less than the estimates provided by this study. Thus, there is some uncertainty in our analysis because of this characteristic of the data. However, the value in this effort lies in developing a regionally consistent, quantitative framework for evaluation the relative liquefaction susceptibility of the Quaternary deposits in the greater St. Louis region. The estimated PGA trigger and susceptibility rating values by map unit are described below.

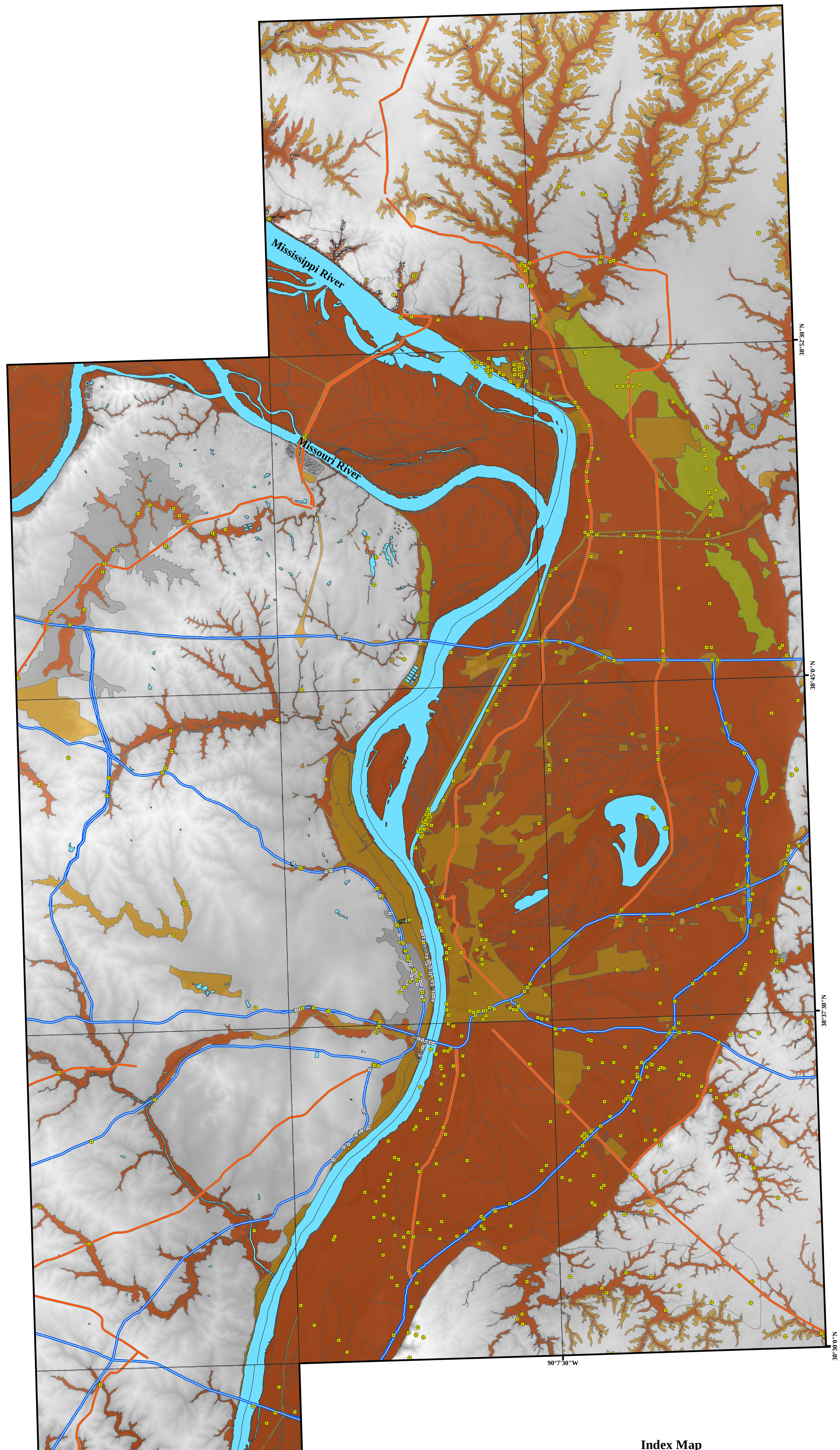
7.1.1 Cahokia Formation (sandy)

This late Holocene granular sediment typically would be considered Very High liquefaction susceptibility based on screening-level analysis because it generally meets the liquefaction criteria of age, texture, depositional environment, and saturation (e.g. Youd and Perkins, 1979). However, the results of the Simplified Procedure analysis indicate this unit as High susceptibility to liquefaction, with an estimated PGA trigger of about 0.20 g (Figure 6, Plate 2). This somewhat milder susceptibility rating suggested from the Simplified Procedure is not un-reasonable, based on the fact that Cahokia alluvium is a relatively poor groundwater source due to its low specific yields (Schict and Buck, 1990). Low specific yield is linked to aquifer porosity, which is a function of void ratio. Seed and Idriss (1971, p. 1250) state that "...the susceptibility of a given soil to liquefaction will be determined to a high degree by its void ratio or relative density." In other words, low void ratios of a unit are associated with relative resistance to liquefaction. As a first-order sensitivity test, we sub-analyzed samples for Cahokia Formation (sand) by culling samples within the upper 10 feet of soil column (proxy for younger floodplain alluvium), by setting all DTW values to zero (full saturation), and re-estimating PGA trigger based on this condition (Figure 6). The data indicate that the relative density of the formation (i.e., $N_{1(60)}$) strongly influences resistance to liquefaction.



- ▲ Cyclic stress ratio for 0.1g peak ground acceleration (PGA)
- ■ Cyclic stress ratio for 0.2g peak ground acceleration (PGA)
- ◆ Cyclic stress ratio for 0.3g peak ground acceleration (PGA)

Figure 6. Simplified Procedure plots of SPT samples by geologic map unit



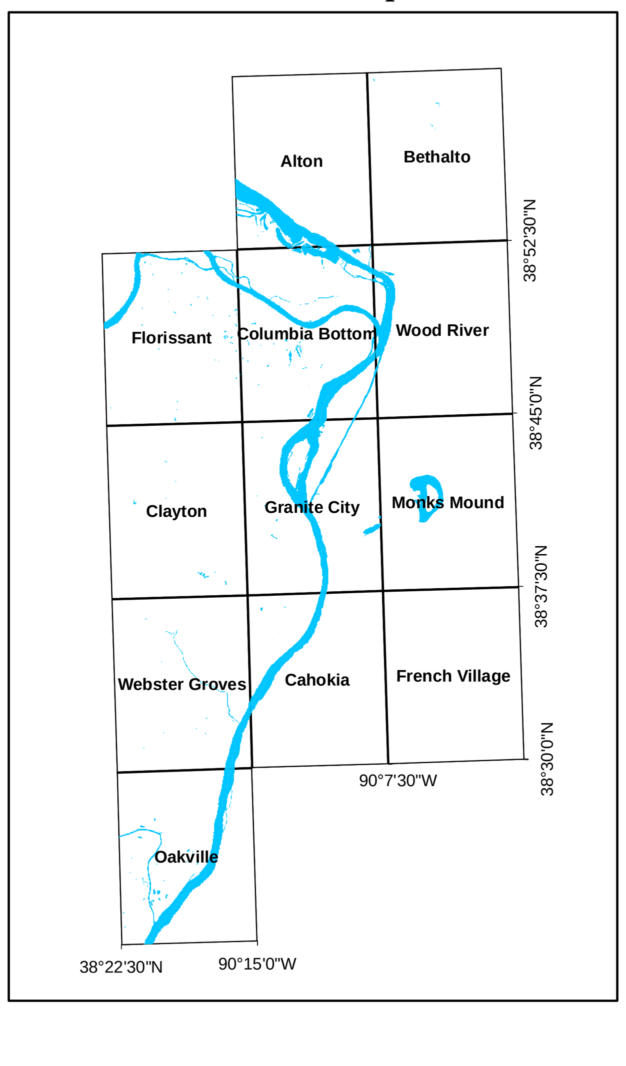
Explanation

Liquefaction susceptibility from estimated liquefaction triggering thresholds based on simplified procedure expressed as gravitational acceleration ("g").

0.20g	*Includes Cahokia Formation (Clay and Sand), and Upland Cahokia Formation (Considered Moderate Liquefaction susceptibility)*
0.25g	*Includes Till, Cahokia (Fan), Artificial Fill, and deposits classified as Disturbed Ground. (Considered Moderate to Low Liquefaction susceptibility)*
0.30g	*Includes Henry Formation (Considered Low Liquefaction susceptibility)*
Loess	*Includes: Peoria Loess and Roxana silt deposits. (Considered Very low Liquefaction susceptibility)*
Equality Formation	*Includes: Cahokia/Equality and Equality Formation deposits. (Considered Very low Liquefaction susceptibility)*
Quarry	
Bed Rock	
Water	

Geotechnical Boring
Stratigraphic Boring
Interstate Highway
State Highway

Index Map



Notes:
- All geologic contacts should be considered approximate.

-Base map is a color-by-elevation Data Elevation Model (DEM).

-The geologic map was constructed at 1:24,000 - scale.

-Enlargement of the map and use at greater scales can result in apparent inacurracies.

-The surficial geologic mapping on the Illinois side of the study area was performed by Illinois State Geological Survey (ISGS). http://www.isgs.uiuc.edu/

-This work was performed under the U.S. Geologic Survey's External Research National Earthquake Hazard Reduction Program **(NEHRP) Grant # 05 - HQGR-0063.**

-The views and conclusions contained in this document are those of the Principal Investigators and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Projection: UTM Zone 15 NAD 83

Probabilistic Liquefaction Potential St. Louis Area

Liquefaction Susceptibility Hazard Map

WILLIAM LETTIS & ASSOCIATES, INC.

Authors: J. Pearce and J. Baldwin

Plate 2

03/31/2008 1722_Susceptibility_033108.mxd 1722 St. Louis

7.1.2 Cahokia Formation (clayey)

As noted in a previous section, this is a cohesive deposit, mostly comprised of silty clay, clayey silt, with some intercalated silt / sandy silt / sandy clay (Unified Soil Classification System classes ML / SM / SC). The overall high fines content (FC) of the unit makes it relatively resistant to liquefaction, but within the deposit are interspersed lenses of coarser grained textures, due to its depositional environment (e.g. alluvial overbank sequences). Low permeability silty clays are a top-stratum "cap" on the underlying granular materials, and could produce elevated pore water pressures when subjected to cyclic stresses from earthquake shaking, and could be a source of liquefaction phenomenon such as sand dikes or sand boils. The Simplified Procedure analysis (Plate 2) suggests an estimated value of 0.20g for the PGA trigger for the SM units (~15% FC), with the $N_{1,60}$ blow counts corrected to a clean sand value (Youd et al., 2001; Cetin et al., 2004; Figure 6). Because the Cahokia Formation (clayey) unit contains occurrences of liquefiable sandy layers (although they are probably not laterally continuous) we assess this unit to be of Moderate liquefaction susceptibility (Plate 2).

7.1.3 Cahokia Formation (upland)

These young alluvial sediments are silty sands (SM) intercalated with overbank silts and clays. Because the deposit is geologically young, generally composed of loose, stratified alluvium, and with anticipated shallow groundwater conditions, it is expected to be liquefiable. The estimated triggering PGA for the sand-rich layers in this map unit is 0.20g (Figure 6), which classifies this map unit as Moderate susceptibility to liquefaction (Plate 2).

7.1.4 Cahokia Formation (fan)

As described in previous section, this map unit has a large silt and clay component due to the re-working and redeposition of silt-rich source materials (i.e., Grimley and Lepley, 1999), whose high fines content (>50%) provide cohesion to the soil. Inspection of borehole stratigraphy confirms that fine-grained sediments are predominant in this map unit. Additionally, groundwater conditions expected in this map unit is about 20 – 30 feet below ground surface (Kolhase, 1987). Therefore, based on the overall loose and unconsolidated nature of the deposit (based on $N_{1(60)}$ values), we estimate a PGA trigger of 0.25 (Figure 6), and assign a susceptibility of Moderate hazard to this map unit (Plate 2).

7.1.5 Henry Formation

This late Pleistocene glacio-fluvial outwash-derived sand and gravel unit is expressed at the ground surface as isolated terrace remnants at the base of the bluffs, near the distal edges of the modern floodplain. The unit is encountered in boring logs primarily at depths of about 30 to 50 feet below ground surface, but is shallower where exposed near the surface, and deeper where buried beneath Holocene alluvium. Beneath 50 feet (15 meters), the samples are not considered liquefiable based on the increased overburden pressures (e.g. Brankman and Baise, 2004; Hengesh and Bachhuber, 1999). The estimated PGA trigger for this unit is 0.30g (Figure 6; Plate 2). About 70% of the Henry Formation samples are shallower than 50 feet below ground surface. Figure 6 also shows the results of the Simplified Procedure for SPT samples of the Henry Formation that are only in the upper 10 feet with DTW set to zero, highlighting the relatively low susceptibility of this unit to liquefaction.

7.1.6 Equality Formation

The Equality Formation, also a late Pleistocene deposit, consists of fine grained sediments (predominantly clays) that are interpreted to have been deposited in slackwater (lacustrine) conditions. As such, we consider the deposit to be cohesive, and, in conjunction with its age, is therefore generally not susceptible to liquefaction. Because the materials are chiefly non-granular, the Simplified Procedure analysis is not appropriate to apply to this unit. SPT samples with sand-rich lithologies are rare within this map unit (Plate 2). We assess this unit to be Very Low susceptibility, based on relative age and overall anticipated electrostatic cohesion of the clay particles. Site-specific studies to evaluate liquefaction susceptibility of this fine-grained unit should be completed to verify the expected response to co-seismic strong ground shaking.

7.1.7 Peoria/Roxanna Formations (Loess)

The loess deposits in the Mississippi valley have a complex history of deposition (e.g. Leigh, 1994; Grimley, 2000; Goodfield, 1965). There are two late Pleistocene loess formations in the study area: the Peoria Silt and the Roxanna Silt. The Roxanna Silt lies stratigraphically beneath the Peoria Silt (and is therefore older), and has a somewhat higher clay content compared to the Peoria Silt (Grimley and Lepley, 1999). However, the units can be difficult to discern from one another in the field or in borehole logs. Therefore, we did not make an attempt to distinguish the individual silt units, and informally lump them together as the same deposit for the Simplified Procedure analysis. The subsurface borehole logs indicate the interpreted loess deposits are largely silt with clay to silty clay component, suggesting fines content of about 85%. The grain size distribution analysis indicates the Peoria Silt as about 25% clay (mostly montmorillonite and illite), 70% silt, and rarely more than 5% sand (Goodfield, 1965, Appendix D). In addition Grimley (2000) presents a very thorough description of the Peoria and Roxanna Silts, and indicates that while the percent illite (< 2μm) content in the Peoria Silt varies through depth, and ranges from about 35 to 55 percent. The Simplified Procedure analysis of SPT samples in relatively sand rich layers (e.g. "sandy loam", SM) encountered in the interpreted loess unit are shown on Plate 2, with blow counts corrected for fines content. The results indicate that the loess should not experience liquefaction even at greater than 0.30g PGA (Plate 2). The Peoria Silt (loess) deposit mantles the entire St. Louis region except for the modern, low-lying floodplain, and some low elevation terrace remnants and alluvial valleys. Occurring mostly atop the bluffs, this unit is typically above the groundwater table. Therefore, due to the high fines content, very high estimate triggering PGAs of the sandy layers (>0.30g), low likelihood of saturation, and the overall age of the deposit, we evaluate this unit as Very Low susceptibility to liquefaction. This susceptibility classification for loess is consistent with the liquefaction hazard evaluation of Shelby County, Tennessee (Van Arsdale and Cox, 2000).

7.1.8 Glasford or Mill Creek Formations (Till)

Till deposits within the study area are rarely exposed at the ground surface, and more commonly found at the near-surface under a veneer of loessal material. Compared to the alluvial Cahokia Formation, there is relatively sparse occurrence of till units in the geotechnical boring logs, indicating that the till has limited sub-aerial extent and vertical thickness in our study area. Till, interpreted from lithologic descriptions, can be as shallow as about 25 feet below ground surface, and is generally encountered deeper, at about 100 – 125 feet below ground surface; well below typically reported liquefaction depths. The deposit age (Pleistocene), fine-grained sedimentary matrix that supports sand and larger clasts, and its encountered depth below ground surface (overburden) will contribute to resistance to liquefaction. However, we cannot preclude this unit from liquefaction because it is likely not completely lithified, and there is some granular material present in the deposit. Based on the Simplified Procedure (Figure 6), we estimate a PGA trigger of 0.25g for this map unit (Plate 2).

7.1.9 Artificial Fill

Non-engineered artificial fill underlies much of the low-lying urban areas adjacent to the Mississippi River. Our subsurface investigation shows that there is considerable variation and complexity in the nature, extent, composition, and geotechnical properties of the artificial fill deposits throughout the St.

Louis region (e.g. glass, brick, cinders, ash, wood, rubble, with/without various amounts of sand or silt). This variability occurs because of the long cultural history of the St. Louis region, and in some instances results from historical post-fire reconstruction of buildings and structures (e.g., great fire of 1852). This complexity of the artificial fill deposits limits our ability to accurately anticipate the response of this deposit to earthquake-induced strong ground motions. There were SPT data we could not include in the analysis because the log of materials information was not sufficient to estimate unit weights or fines content of the fill. For the samples we could analyze, the Simplified Procedure suggests a PGA trigger of about 0.25g (Figure 6). Thus, the liquefaction susceptibility of the artificial fill likely locally ranges from Low (e.g. silty-clay fill) to Very High (e.g. rubble and urban detritus, loosely piled fine sand and silt). Therefore, artificial fill should be conservatively considered to be moderately susceptible to liquefaction until demonstrated otherwise by site-specific studies.

7.1.10 Artificial Embankment Fill

This map unit (Qafe) is inferred to have been emplaced in accordance with modern engineering principles and practices (e.g. compaction ratios, dry densities), based on the relative recency of construction, and the volume of earth moving, filling, or grading needed to produce the engineered berms observable on 1:24,000-scale topographic map. In Illinois, based on inspection of available Army Corps boring logs, the Chain of Rocks canal levee material is composed largely of low hydraulic conductivity silts and clays, and could, but not necessarily, potentially be resistant to liquefaction as a result of higher fine contents. Because we lack direct SPT data for the levee structures, the relative density of the levee material is not accurately known, and thus there is some uncertainty in the liquefaction analysis of this map unit with respect to the levee deposits. Additional data and investigation with respect to the levee properties would help reduce some of the uncertainty in the assessment of anticipated response to strong ground shaking. In Missouri, the road fill prisms shown on the geologic map typically overlie areas of relatively deep groundwater (e.g. loess-capped uplands), and are also elevated about the pre-existing ground elevation. Therefore, we consider these units to be of Moderate susceptibility to liquefaction (trigger of 0.25g) based on their inferred engineering characteristics (e.g. Hengesh and Bachhuber, 2004); however, site-specific geotechnical studies should be performed to more fully characterize the liquefaction susceptibility of this deposit.

7.2 Probabilistic liquefaction potential

This section describes the results of the probabilistic liquefaction potential analyses that evaluates the triggering threshold estimates against ground motion values at two levels of probability: the 2% probability of exceedance in 50 years ("2500-year return interval") and the 10% probability of exceedance in 50 years ("500-year return interval"). The ground motion PGA values used in this study are from the USGS National Seismic Hazard maps (Frankel et al., 2002; Figure 5). Overall, the end result of this analysis is a function of the estimated PGA triggering value, as well as the distribution and magnitude of the anticipated PGA from a seismic event of a given exceedance probability. Rather than depicting the result of the analysis as a binary (i.e., yes/no) hazard map, this study portrays the liquefaction potential in terms of percent PGA above or below the triggering threshold. That is, the magnitude of the probabilistic PGA value above or below the PGA trigger, divided by the PGA trigger and expressed as percent. For example: a geologic map unit with an estimated PGA trigger of 0.18g in an area with an anticipated PGA of 0.20g would have a liquefaction exceedance potential of about 11% ([0.02/0.18] * 100). Negative percentage values indicate insufficient PGA for triggering liquefaction. Below we describe the results of the 10% in 50yr probabilistic liquefaction potential analysis followed by the results of the 2% in 50yr probabilistic liquefaction potential analysis.

7.2.1 Liquefaction potential at the 10% probability of exceedance in 50 years

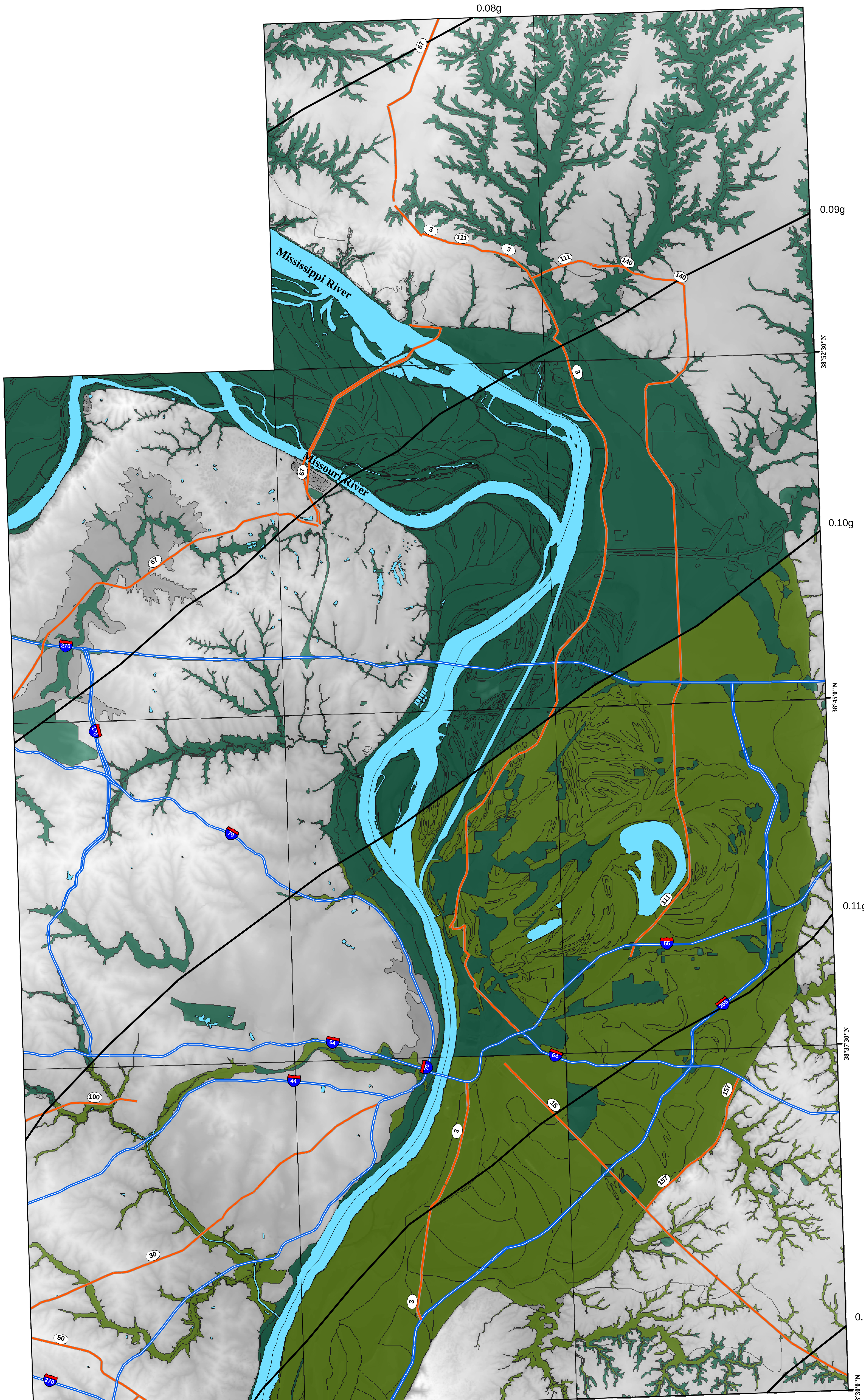
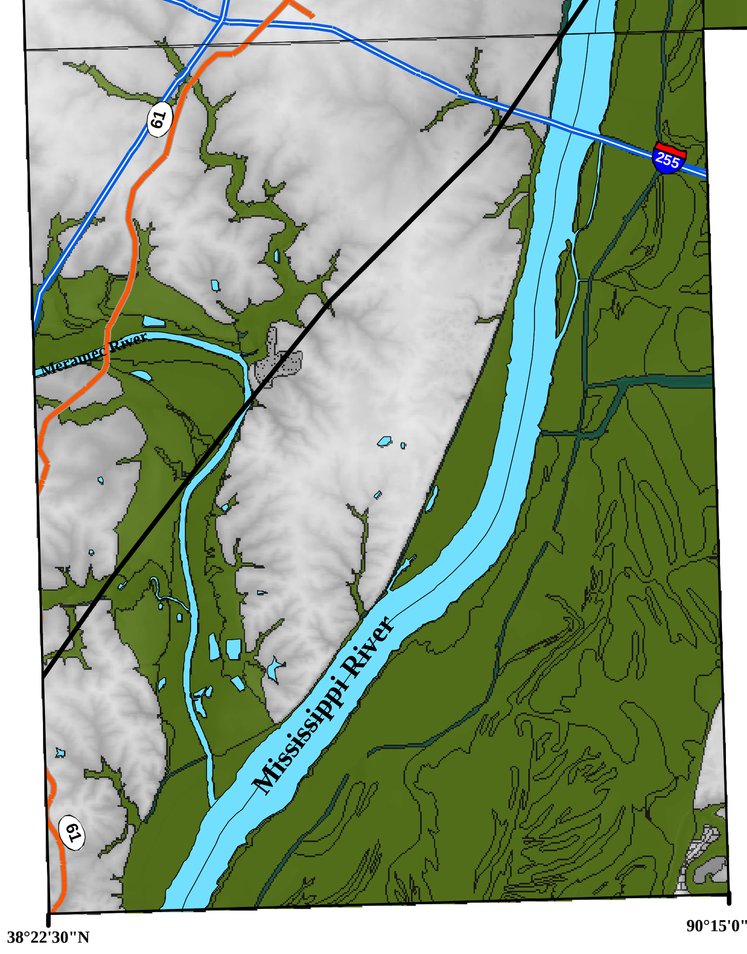
Within the study area, peak acceleration (PGA) at 10% probability of exceedance in 50 years ranges from 0.12 to 0.08 g, decreasing from southeast to northwest (Figure 5; Plate 3). This research finds that the estimated PGA triggering values (i.e., susceptibility) are consistently greater than the forecast PGA values (Frankel et al., 2002). The estimated PGA trigger for the susceptible geologic map units (Plate 2) are at least 40% greater than the forecast PGA values for this probabilistic event (Figure 5; Plate 3). Thus, the potential for liquefaction based on this probability and magnitude of seismic ground shaking is very low to none.

It is possible that the relatively deeper (e.g., 30 feet below ground) alluvial sediments beneath the valley floor have experienced substantial aging affects, including partial cementation or packing of clasts (reduction in void space) resulting from previous Holocene seismic loading events (e.g., 1811-1812, and earlier). Establishment of detailed floodplain vertical accretion rates within the American Bottoms may constrain depths of young unconsolidated granular material, and thus hone in on the most sensitive stratigraphic layer.

This analysis does not, however, preclude liquefaction processes at this probability and magnitude of seismic ground shaking. Additionally, artificial fill material is challenging to characterize, because of the large variability in type of fill material and method of material emplacement, both locally and regionally. This study recommends further studies that specifically evaluate the fill characteristics and the potential response of artificial fill units to seismic loading.

7.2.2 Liquefaction potential at the 2% probability of exceedance in 50 years

The peak acceleration (PGA) within the study area at 2% probability of exceedance in 50 year ranges from 0.33 to 0.22g, also decreasing along a northwest trend (Figure 5; Plate 4). These values are about three times greater than those of at the 10% in 50yr probability level. The estimated PGA triggering values (i.e., susceptibility) are consistently less than the probabilistic PGA values, indicating extensive potential for liquefaction throughout the valley floor and within tributary upland alluvium (Plate 4). Within the Oakville, Webster Groves, Cahokia, and French Village quadrangles, the modeled PGA values (Frankel et al., 2002) exceed estimated triggering threshold of the alluvial deposits by 40 to 50%, and thus have the greatest liquefaction potential within the overall study area (Plate 4). The potential for liquefaction, while commonly above the triggering threshold, decreases in the northwest direction in conjunction with PGA decrease. PGA exceedance of triggering estimates is not more than 10% in much of the Elsah, Bethalto, and Florissant quadrangles (Plate 4). Alluvium of tributary creeks has a high percent exceedance in the southern study area, about 30 to 49% (e.g., Meramec River), but also decreases northwesterly with PGA. This is consistent with previous paleo-liquefaction studies in the Meramec River drainage (e.g. Tuttle et al., 1999). Within the French Village and Bethalto quadrangles, the Cahokia Formation (fan) has notably lower percent exceedance, and is, in some areas, below the 2% chance PGA indicating very low to no liquefaction potential. This is largely controlled by the PGA distribution, and also by the groundwater depression cone present in this area from aquifer pumping, lowering local DTW (e.g. Kolhase, 1987).

Explanation

Liquefaction Potential
Based on 10% chance in 50 year
Peak Ground Accelerations

Increasing Liquefaction Potential

- >50%
- 40 to 50%
- 30 to 40%
- 20 to 30%
- 10 to 20%
- 0 to 10%

Potentially liquefiable; expressed as percent PGA exceedence above estimated liquefaction triggering acceleration.

Liquefaction threshold

Decreasing Liquefaction Potential

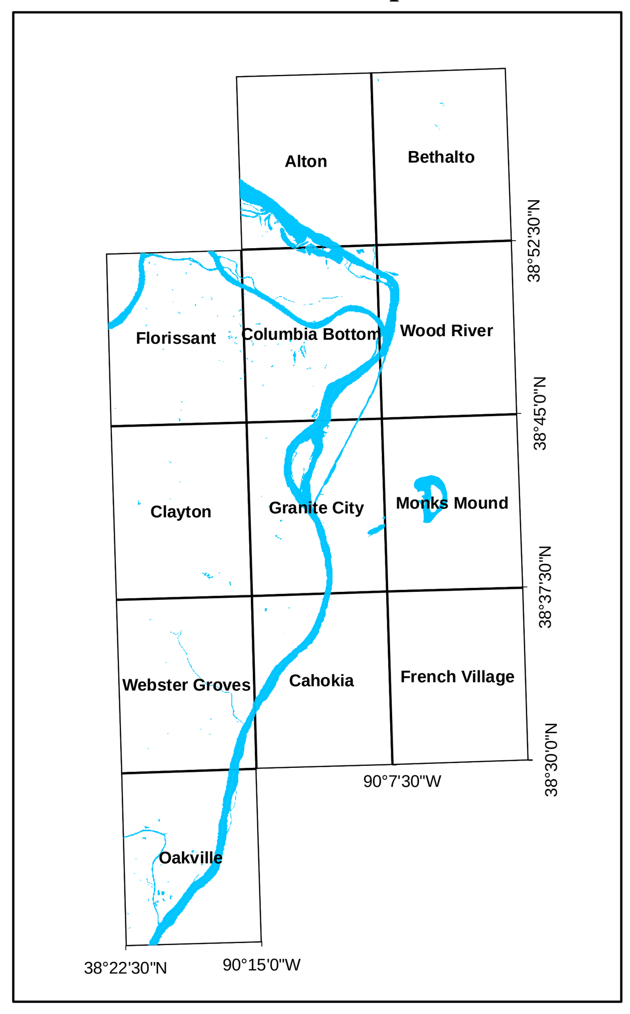
- 0 to 10%
- 10 to 20%
- 20 to 30%
- 30 to 40%
- 40 to 50%
- >50%

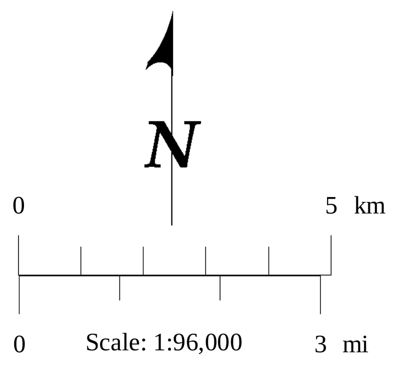
Potentially un-liquefiable; expressed as percent PGA below the estimated liquefaction triggering acceleration.

- Bed Rock
- Equality
- Loess
- Quarry
- Water
- Interstate Highway
- State Highway
- 0.10g PGA (isoseismal) contour line. From USGS National Seismic Hazard Map 10% chance in 50 years (Frankel et al., 2002). Values are units of acceleration expressed as a fraction of gravity.

Note: 10% in 50 Liquefaction potential = (PGA-Trigering Val)/Triggering Val.

Index Map





Notes:
- All geologic contacts should be considered approximate.

-Base map is a color-by-elevation Data Elevation Model (DEM).

-The geologic map was constructed at 1:24,000 - scale.

-Enlargement of the maps and use at greater scales can result in apparent inaccurracies.

-The surficial geologic mapping on the Illinois side of the study area was performed by Illinois State Geological Survey (ISGS). http://www.isgs.uiuc.edu/

-This work was performed under the U.S. Geologic Survey's External Research National Earthquake Hazard Reduction Program **(NEHRP) Grant # 05 - HQGR-0063.**

-The views and conclusions contained in this document are those of the Principal Investigators and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Projection: UTM Zone 15 NAD 83

Probabilistic Liquefaction Potential
St. Louis Area

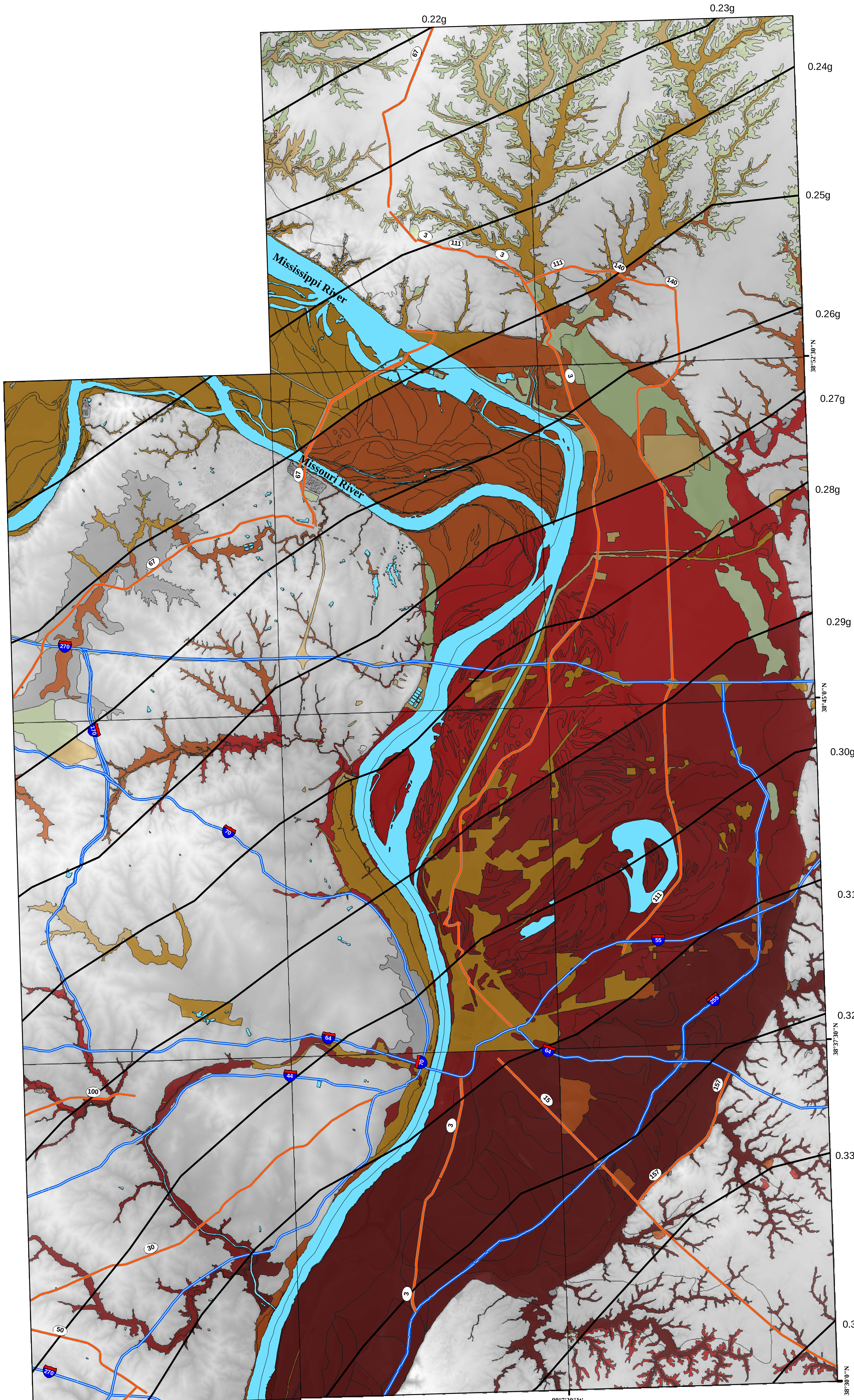
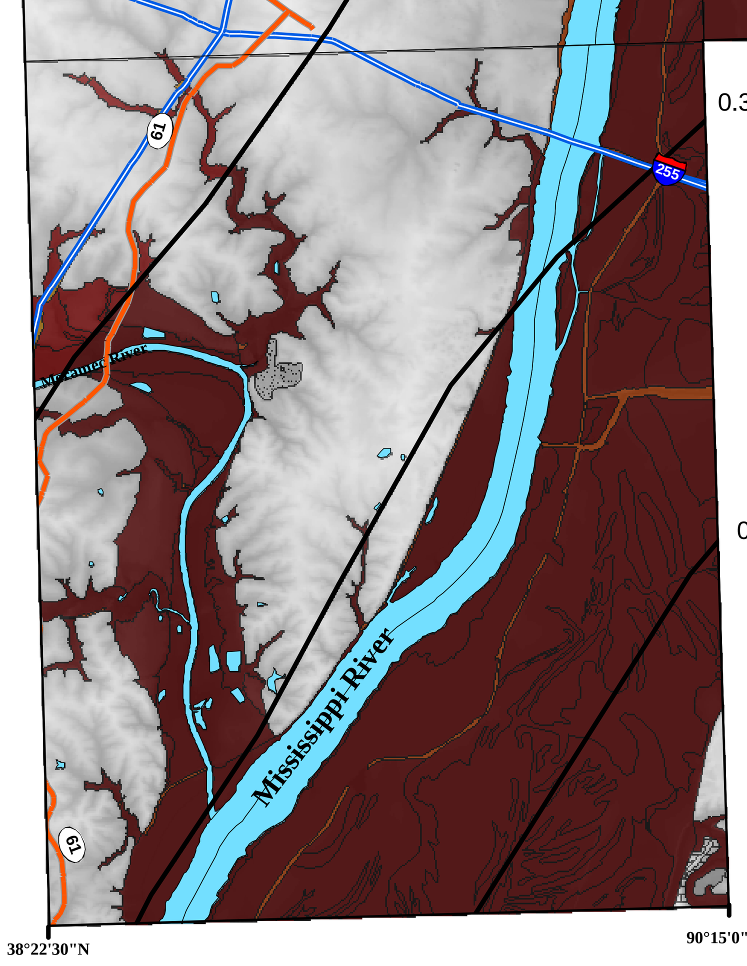
Probabilistic Liquefaction Potential
Based on 10% Chance in 50 years PGA

WLA William Lettis & Associates, Inc.

Plate 3

Authors: J. Pearce and J. Baldwin

03/31/2008 1722_10_in_50_033108.mxd 1722 St. Louis

Explanation

Liquefaction Potential
Based on 2% chance in 50 year
Peak Ground Accelerations

Increasing Liquefaction Potential
- >50%
- 40 to 50%
- 30 to 40%
- 20 to 30%
- 10 to 20%
- 0 to 10%

Potentially liquefiable; expressed as percent PGA exceedence above estimated liquefaction triggering acceleration.

Liquefaction threshold

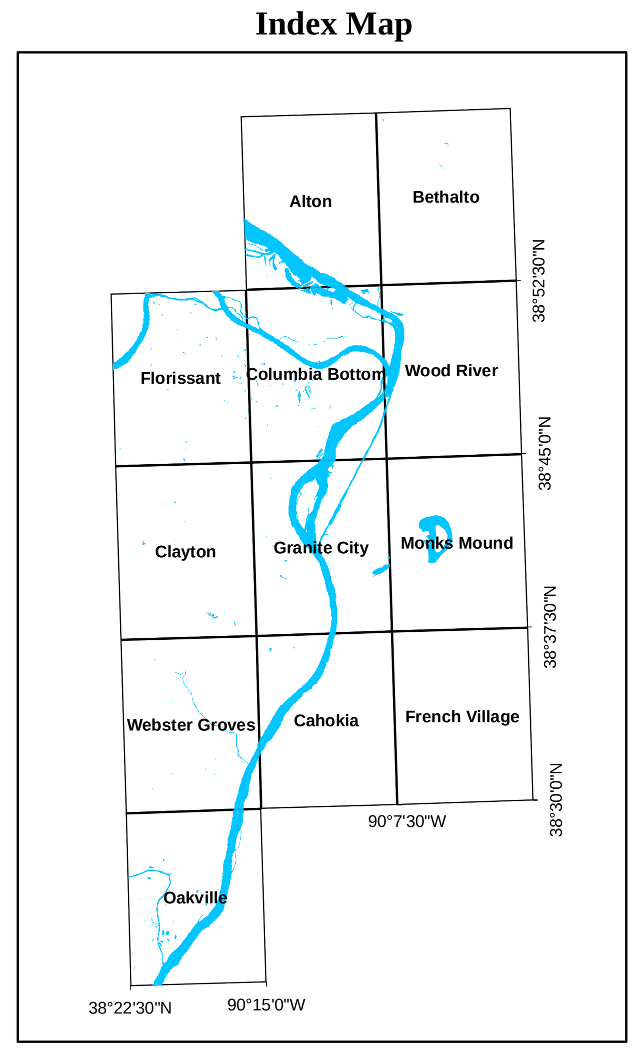
Decreasing Liquefaction Potential
- 0 to 10%
- 10 to 20%
- 20 to 30%
- 30 to 40%
- 40 to 50%
- >50%

Potentially un-liquefiable; expressed as percent PGA below the estimated liquefaction triggering acceleration.

- Bed Rock
- Equality
- Loess
- Quarry
- Water
- Interstate Highway
- State Highway
- 0.34g PGA (isoseismal) contour line. From USGS National Seismic Hazard Map 2% chance in 50 years (Frankel et al., 2002). Values are units of acceleration expressed as a fraction of gravity.

Note: 2% in 50 Liquefaction potential = (PGA-Trigering Val)/Triggering Val.

Index Map



N

0 5 km

Scale: 1:96,000

0 3 mi

Notes:
- All geologic contacts should be considered approximate.

-Base map is a color-by-elevation Data Elevation Model (DEM).

-The geologic map was constructed at 1:24,000 - scale.

-Enlargement of the map and use at greater scales can result in apparent inaccurracies.

-The surficial geologic mapping on the Illinois side of the study area was performed by Illinois State Geological Survey (ISGS). http://www.isgs.uiuc.edu/

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Projection: UTM Zone 15 NAD 83

Probabilistic Liquefaction Potential
St. Louis Area

Probabilistic Liquefaction Potential
Based on 2% Chance in 50 years PGA

WLA William Lettis & Associates, Inc.

Plate 4

Authors: J. Pearce and J. Baldwin

03/31/2008 1722_02_in_50_033108.mxd 1722 St. Louis

8.0 DISCUSSION

Our liquefaction susceptibility and probabilistic liquefaction potential hazard maps for the St. Louis region show a range of hazard levels for the study area, due in large part to the geologic deposits, depositional environments, and physical properties of the unconsolidated sediments, and the earthquake scenarios evaluated (Plates 2, 3, and 4). This study shows that the estimated highest potential for liquefaction occurs in the southern parts of the map area (e.g., Plate 4), and is consistent with documented paleoliqefaction occurrence within the Meramec River drainage (Tuttle et al., 1999), and limited CPT analysis of sediments in this drainage (Mayne, 2001).

By and large, the geologic deposits within the study area are typically considered as having all the necessary ingredients for liquefaction potential; that is: Holocene granular alluvium with shallow groundwater conditions that are within active seismic source areas. The analysis completed for this study indicates that alluvium commonly is medium dense to dense, even at shallow depths, and is relatively resistant to liquefaction (Plate 2). This resistance to liquefaction can be attributed to: (1) original, or primary, close packing of the granular matrix, such that void space is low, and grain-to-grain contact is very tight; (2) "aging" effects, such as partial cementation of the soil column that could increase overall binding or cohesion; (3) prior earthquake events in the region (e.g., Tuttle et al., 1999), that may serve to reduce subsequent liquefaction susceptibility (i.e., secondary, post-depositional packing of matrix). Examination of the Simplified Procedure plots (Plate 2) shows a fair amount of vertical spreading of the data within the alluvial deposits, indicating a possible range of selectable PGA trigger estimates. At the same time, the data also show an abundance of data points lying well to the right of the threshold curves, indicating that much of the sample population would not be susceptible to liquefaction even at very high PGA values. This is holds even when more conservative conditions are analyzed, including a fully saturated soil column and restriction of data to samples with the upper 20 feet of the soil column (Plate 2). In this way, while the granular river alluvium conceptually would be considered highly susceptible to liquefaction, the empirical data and analysis of this research consistently do not bear this out. Additionally, the susceptibilities of sub-divided Quaternary alluvium (e.g. Cahokia Formation) are relatively consistent with each other. That is, there is not a dramatic difference in estimated PGA trigger values (susceptibility) between individual map units (Plate 2). This suggests that, when taken as a whole, the floodplain alluvium may be respond more uniformly than expected. Alternatively, this similarity between map unit susceptibility could also be attributed to the vertical spread of data in the Simplified Procedure plots, which effectively "washes out" the site-specific geotechnical variability of the floodplain deposits.

Soil stratigraphy can exert an important control on the occurrence of liquefaction. For example, the presence of a fine-grained stratum overlying liquefiable sand can act to confine and elevate pore pressures during cyclic shaking until sufficient head develops such that the water erupts through the confining bed, and creates a sand boil or blow though the soil. Because floodplain depositional environments are dynamic, with river migration, erosion, deposition, and re-working of sediment, the subsurface soil stratigraphy will be correspondingly complex. That is, the type and sequence of soil deposits will be laterally variable and inconsistent from one location to another. Because of this complexity, there may be instances where the local site ground conditions will not match our basic stratigraphic model, which provides a conceptual framework of floodplain stratigraphy as: Paleozoic bedrock overlain by Pleistocene sands and gravels, in turn overlain by Holocene interbedded sand, silt, and clay.

Based on our analysis, the 10% probability of exceedance PGA is insufficient to trigger liquefaction in the study area, and the PGA triggers fall well below anticipated shaking (Plate 3). This seismic hazard probability level is commonly used in building code regulatory criteria, and also is generally consistent with broadly-constrained estimates of NMSZ recurrence intervals (~500 years). Previous paleo-liquefaction studies (e.g., McNulty and Obermeier, 1999; Tuttle et al., 1999) have documented localized instances of paleo-liquefaction features (e.g., sand boils, sand dikes, or sand flows) within drainages tributary to the Mississippi River, however, to date, the authors have not found maps or historical reports that document or describe abundant and widespread paleo-liquefaction features within the floodplain deposits in the study area. This does not necessarily mean that widespread liquefaction did not historically occur in the St. Louis region as a result of strong ground shaking; rather, it should be interpreted that compelling evidence either for the occurrence or for the absence of liquefaction features within the valley alluvium is not forthcoming. Additionally, while the Mississippi River alluvial sediments may have experienced some degree of liquefaction from the 1811-1812 NMSZ earthquakes, because the uppermost deposits post-date 1811-1812, the liquefaction features potentially associated with this event could be either eroded or buried by historical meandering of the Missouri and Mississippi Rivers.

Plate 4 shows that the liquefaction potential for the 2% chance of exceedance in 50 yr ground motion is fairly high across much of the study area, which is not unexpected at this conservative probability level. This analysis also shows that the liquefaction potential decreases with decreasing PGA along a north-northwest trend, from over 50% liquefaction threshold exceedance in the south of the study area, to about 10% liquefaction threshold exceedance in the northern study area. This distribution of liquefaction potential suggests that infrastructure or facilities located in the southern portion of the study area may experience more effects from seismically-induced liquefaction than the northern counterparts (Plate 4). This also suggests that emergency response plans should consider an approach or prioritization that accounts for this anticipated decrease in liquefaction potential from south to north across the study area, to be best prepared for, or to respond after, a large seismic event.

9.0 CONCLUSIONS

Based on the results of our analyses that incorporates geologic criteria (e.g. Youd and Perkins, 1987) and quantitative geotechnical criteria (e.g. Seed and Idriss, 1971) with seismic hazard criteria (e.g. Frankel, et al. 2002), we conclude the following:

(1) The alluvial deposits are moderately resistant to liquefaction, even at conservative DTW conditions, and have relatively consistent liquefaction triggering thresholds;

(2) Liquefaction potential at the 10% in 50 years probability is very low throughout the study area;

(3) Liquefaction potential at the 2% in 50 years probability level is overall high, and sufficient to anticipate liquefaction throughout much of the study area;

(4) Probabilistic liquefaction potential decreases from south to north across the region, for both scenarios evaluated; and,

(5) The distribution and magnitude of liquefaction potential is predominantly controlled by estimated strong ground motion and, to a lesser degree, surficial geologic deposits.

9.1 Future Research

Future research that would refine our liquefaction hazard results would incorporate state-of-the-science ground motion and amplification/attenuation models. For instance, new ground motion seismic hazard maps have just recently been published by USGS (i.e., Frankel, et al., 2007) and add more sophistication to ground motion hazard maps used in this analysis (Frankel et al., 2002). Future liquefaction research should incorporate these new maps, as it will allow more detailed analysis of liquefaction potential based on earthquake spectra, period of ground shaking, and other variables. Also, the St. Louis region lies north of the Mississippi Embayment, and therefore has a thinner amount of unconsolidated overburden above the bedrock. Atkinson and Beresnev (2002) indicate that this difference in overburden thickness would affect the ground motion responses (e.g. peak accelerations and frequencies) between Memphis and St. Louis, for the same scenario earthquake, because of differences in energy amplification and attenuation that are a function of the soil column properties (e.g. shear wave velocity). Next-generation attenuation models (e.g., Boore and Atkinson, 2006) should be incorporated to further refine the liquefaction potential hazard mapping.

Additional future work that would refine our liquefaction hazard results would include:

- incorporate most recently updated ground motion and amplification/attenuation model
- geostatistical and heuristic analysis of the data populations used in the Simplified Procedure
- improved laboratory data on fines content of geologic deposits
- augmented shear wave data
- assess if geographical locations influence the geologic characteristics
- evaluate the potential magnitudes and locations of permanent ground deformation that could be associated with seismically-induced liquefaction.

9.2 Limitations

As with many regional studies, certain assumptions and generalizations were necessary in order to perform the analysis. Shear wave velocities used for each map unit represents an average of the ranges measured, and can therefore be a source of uncertainty. Unit weights and percent fines content of the samples used in the Simplified Procedure are, in several instances, estimated based on the soil description and USCS classification in the log of boring. Scenario depth-to-groundwater values used in this study may not match instantaneous static water level measurements, and may therefore introduce a level of uncertainty to the analysis. This study does not assess the possible locations or magnitudes of permanent ground deformation resulting from seismically-induced liquefaction. Lastly, this research represents quantitative liquefaction potential hazard evaluation that can be used as planning-level framework for seismic hazard preparation, mitigation, and early response plans. Ultimately, site specific studies should be performed to fully assess and verify the anticipated soil response to seismic loading if precise investigations are required for critical facilities or infrastructure.

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11.0 INFORMATION DISSEMINATION

As part of item G.3 Final Report and Dissemination, we have accomplished the following during our research efforts:

- Presentation at St. Louis Seismic Hazards Working Group committee meeting (April, 2004)

- Presentation at Geological Society of America, Central US Section Meeting
  Pearce, J.T., and Baldwin, J.N., (2004). Liquefaction susceptibility mapping St. Louis, Missouri and Illinois: [abs] Geological Society of America North-Central Section Meeting Abstracts with Programs

- Invited speaker on the Inaugural Earthquake Insights Field Trip which increases awareness and understanding of earthquake risks in the Central US among key audience of planners and decision-makers (2005).

- Presentation to St Louis Area Earthquake Hazards Mapping Program working group (SLAEHMP)

- Information collaboration with other relevant NEHRP studies, and we have disseminated this report and the accompanying liquefaction hazard maps and data to academics and practitioners in the Central US

    - NEHRP 05HQGR0014 Regional seismic hazards information transfer to executive policymakers and private-sector leaders

    - NEHRP 05HQGR0103 (L. Biase, Principal Investigator, Tufts University)

    - MAE Center's seismic loss assessment project (L. Cleveland, University of Illinois Urbana-Champaign)